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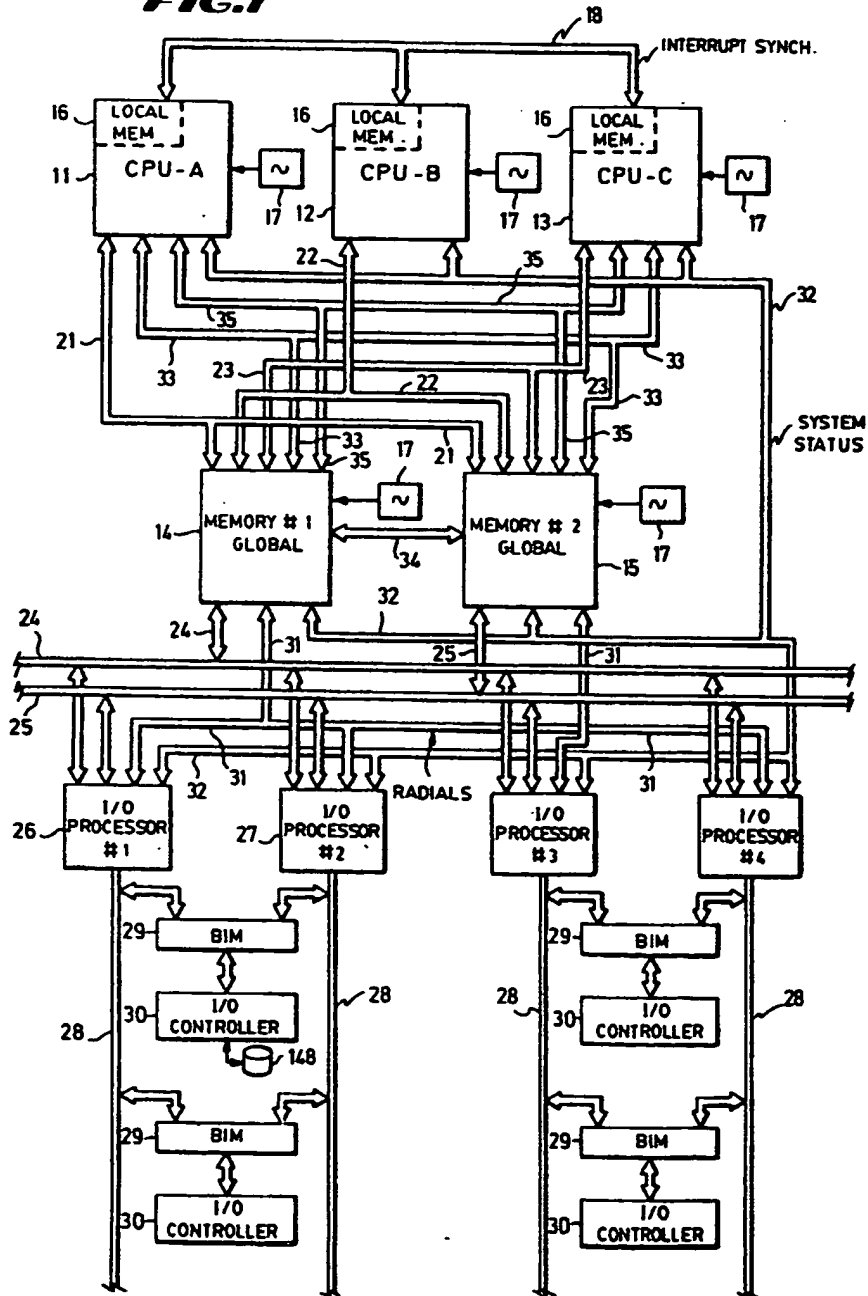
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(54) Fault-tolerant computer system with/config filesystem.

(57) A computer system in a fault-tolerant configuration employs multiple identical CPUs executing the same instruction stream, with multiple, identical memory modules in the address space of the CPUs storing duplicates of the same data. The system detects faults in the CPUs and memory modules, and places a faulty unit offline while continuing to operate using the good units. The faulty unit can be replaced and reintegrated into the system without shutdown. The computer system employs a power supply system including a battery backup so that upon AC power failure the system can execute an orderly shutdown, saving state to disk. A restart procedure restores the state existing at the time of power failure if the AC power has been restored by the time the shutdown is completed. The system employs a pseudo-filesystem to dynamically manage the hardware components. A directory which appears as a standard, hierarchical directory in this filesystem contains a file for

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each component; each file maps to either a hardware component or a software module. The pseudo-filesystem hierarchy is determined during system initialization and is automatically updated whenever the software or hardware configuration changes. The pseudo-filesystem, called /config filesystem herein, is implemented as a Unix filesystem in the Unix filesystem switch. The multiple CPUs are loosely synchronized, as by detecting events such as memory references and stalling any CPU ahead of others until all execute the function simultaneously; interrupts can be synchronized by ensuring that all CPUs implement the interrupt at the same point in their instruction stream. Memory references via the separate CPU-to-memory busses are voted at the three separate ports of each of the memory modules. I/O functions are implemented using two identical I/O busses, each of which is separately coupled to only one of the memory modules. A number of I/O processors are coupled to both I/O busses. I/O devices are accessed through a pair of identical (redundant) I/O processors, but only one is designated to actively control a given device; in case of failure of one I/O processor, however, an I/O device can be accessed by the other one without system shutdown.

**FIG. 1**

# **FAULT-TOLERANT COMPUTER SYSTEM WITH ONLINE REINTEGRATION AND SHUTDOWN/RESTART**

## **BACKGROUND OF THE INVENTION**

This invention relates to computer systems, and more particularly to detection and reintegration of faulty components, to a shutdown and restart procedure in the event of a power failure, and file system  
 5 used for configuring the functions, all in a fault-tolerant multiprocessor system.

Highly reliable digital processing is achieved in various computer architectures employing redundancy. For example, TMR (triple modular redundancy) systems may employ three CPUs executing the same instruction stream, along with three separate main memory units and separate I/O devices which duplicate functions, so if one of each type of element fails, the system continues to operate. Another fault-tolerant  
 10 type of system is shown in U.S. Patent 4,228,496, issued to Katzman et al, for "Multiprocessor System", assigned to Tandem Computers Incorporated. Various methods have been used for synchronizing the units in redundant systems; for example, a method of "loose" synchronizing has been disclosed, in contrast to other systems which have employed a lock-step synchronization using a single clock, as shown in U.S. Patent 4,453,215 for "Central Processing Apparatus for Fault-Tolerant Computing", assigned to Stratus  
 15 Computer, Inc. A technique called "synchronization voting" is disclosed by Davies & Wakerty in "Synchronization and Matching in Redundant Systems", IEEE Transactions on Computers June 1978, pp. 531-539. A method for interrupt synchronization in redundant fault-tolerant systems is disclosed by Yondea et al in Proceeding of 15th Annual Symposium on Fault-Tolerant Computing, June 1985, pp. 246-251, "Implementation of Interrupt Handler for Loosely Synchronized TMR Systems". U.S. Patent 4,644,498 for  
 20 "Fault-Tolerant Real Time Clock" discloses a triple modular redundant clock configuration for use in a TMR computer system. U.S. Patent 4,733,353 for "Frame Synchronization of Multiply Redundant Computers" discloses a synchronization method using separately-clocked CPUs which are periodically synchronized by executing a synch frame.

An important feature of a fault-tolerant computer system such as those referred to above is the ability  
 25 for processes executing on the system to survive a power failure without loss or corruption of data. One way of preventing losses due to power failure is, of course, to prevent power failure; to this end, redundant AC power supplies and battery backup units may be provided. Nevertheless, there is a practical limit to the length of time power may be supplied by battery backup units, due to the cost, size and weight of storage batteries, and so it may be preferable to provide for orderly system shutdown upon AC power failure.

As high-performance microprocessor devices have become available, using higher clock speeds and providing greater capabilities, and as other elements of computer systems such as memory, disk drives, and the like have correspondingly become less expensive and of greater capability, the performance and cost of high-reliability processors have been required to follow the same trends. In addition, standardization on a few operating systems in the computer industry in general has vastly increased the availability of  
 30 applications software, so a similar demand is made on the field of high-reliability systems; i.e., a standard operating system must be available.

The fault-tolerant computer systems of the type shown in these prior patents and publications have used custom-designed operating systems and applications software written especially for each system, rather than using more generalized operating systems so that widely available applications software could  
 40 be employed. Thus, the variety of applications software has been limited, and that available has been expensive. For this reason, a system as illustrated herein is intended to make use of a standard operating system, Unix™.

In a fault-tolerant computer system having redundant modules, the system can continue to operate in a wide variety of configurations. CPU modules, memory modules or I/O modules may be removed from the  
 45 system while the remaining component parts continue to operate. At any given time, however, the operating system must have an accurate record of what the system configuration is, i.e., what modules are present and operating in full capacity. Examining the configuration of a Unix™ system presents difficulties, however. Usually a /dev entry is employed for this purpose, but /dev entries tell what could be installed, not what is installed. Unix system traditionally access hardware components and software modules through a series of special files (the /dev entries). These files must be created by a system administrator and must be  
 50 explicitly modified whenever the system configuration changes.

It is therefore the principal object of this invention to provide an improved high-reliability computer system, particularly of the fault-tolerant type. Another object is to provide an improved redundant, fault-tolerant type of computing system, and one in which high performance and reduced cost are both possible; particularly, it is preferable that the improved system avoid the performance burdens usually associated

with highly redundant systems. A further object is to provide a high-reliability computer system in which the performance, measured in reliability as well as speed and software compatibility, is improved but yet at a cost comparable to other alternatives of lower performance. An additional object is to provide a high-reliability computer system which is capable of executing an operating system which uses virtual memory management with demand paging, and having protected (supervisory or "kernel") mode; particularly an operating system also permitting execution of multiple processes; all at a high level of performance. Still another object is to provide a high-reliability redundant computer system which is capable of detecting faulty system components and placing them off-line, then reintegrating repaired system components without shutting down the system. Another object of this invention to provide an improved power-failure procedure in a high-reliability computer system, particularly of the fault-tolerant type. An additional object is to provide improved operation of a redundant, fault-tolerant type of computing system in power-fail situations, and one in which reliability, high performance and reduced cost are possible. It is an additional object of this invention to provide an improved method of operating a high-reliability computer system, particularly of the fault-tolerant type. Another object is to provide improved operation of a redundant, fault-tolerant type of computing system in situations where faulty hardware components may be removed from the system and replaced while the system continues to operate, and one in which reliability, high performance and reduced cost are possible.

#### SUMMARY OF THE INVENTION

In accordance with one embodiment of the invention, a computer system employs three identical CPUs typically executing the same instruction stream, and has two identical, self-checking memory modules storing duplicates of the same data. Memory references by the three CPUs are made by three separate busses connected to three separate ports of each of the two memory modules. In order to avoid imposing the performance burden of fault-tolerant operation on the CPUs themselves, and imposing the expense, complexity and timing problems of fault-tolerant clocking, the three CPUs each have their own separate and independent clocks, but are loosely synchronized, as by detecting events such as memory references and stalling any CPU ahead of others until all execute the function simultaneously; the interrupts are also synchronized to the CPUs ensuring that the CPUs execute the interrupt at the same point in their instruction stream. The three asynchronous memory references via the separate CPU-to-memory busses are voted at the three separate ports of each of the memory modules at the time of the memory request, but read data is not voted when returned to the CPUs.

The two memories both perform all write requests received from either the CPUs or the I/O busses, so that both are kept up-to-date, but only one memory module presents read data back to the CPUs in response to read requests; the one memory module producing read data is designated the "primary" and the other is the back-up. Both memories present read data back to the I/O processors (IOP's) in response to I/O requests. The memory requests to the two memory modules are implemented while the voting is still going on, so the read data is available to the CPUs a short delay after the last one of the CPUs makes the request. Even write cycles can be substantially overlapped because DRAMs used for these memory modules use a large part of the write access to merely read and refresh, then if not strobed for the last part of the write cycle the read is non-destructive, therefore, a write cycle begins as soon as the first CPU makes a request, but does not complete until the last request has been received and voted good. These features of non-voted read-data returns and overlapped accesses allow fault-tolerant operation at high performance, but yet at minimum complexity and expense.

I/O functions are implemented using two identical I/O busses, each of which is separately coupled to only one of the memory modules. A number of I/O processors are coupled to both I/O busses, and I/O devices are coupled to pairs of the I/O processors but accessed by only one of the I/O processors at a time. The CPUs can access the I/O processors through the memory modules (each access being voted just as the memory accesses are voted), but the I/O processors can only access the memory modules, not the CPUs; the I/O processors can only send interrupts to the CPUs, and these interrupts are collected in the memory modules before being presented to the CPUs. If an I/O processor fails, the other one of the pair can take over control of the I/O devices for this I/O processor via system software by manipulating certain control registers resident on the CPU, memory modules, and remaining I/O processor and by altering operating system data structures. In this manner, fault tolerance and reintegration of an I/O device is possible without system shutdown.

The memory system used in the preferred embodiment is hierarchical at several levels. Each CPU has its own cache, operating at essentially the clock speed of the CPU. Then each CPU has a local memory not accessible by the other CPUs, and virtual memory management allows but does not require the kernel of

the operating system and pages for the current task to be in local memory for all three CPUs, accessible at high speed without overhead of voting imposed. Next is the memory module level, referred to as global memory, where voting and synchronization take place so some access-time burden is introduced; nevertheless, the speed of the global memory is much faster than disk access, so this level is used for page swapping with local memory to keep the most-used data in the fastest area, rather than employing disk for the first level of demand paging. Global memory is also used as a staging area for DMA accesses from I/O controllers.

One of the features of the disclosed embodiment of the invention is the ability to replace faulty redundant units or FRU's (CPUs, Memory Modules, IOPs, Battery Modules, I/O Controllers, etc.) without shutting down the system. Thus, the system is available for continuous use even though components may fail and have to be replaced. In addition, the ability to obtain a high level of fault tolerance with fewer system components, e.g., no fault-tolerant clocking needed, only two memory modules needed instead of three, voting circuits minimized, etc., means that there are fewer components to fail, and so the reliability is enhanced. That is, there are fewer failures because there are fewer components, and when there are failures the components are isolated to allow the system to keep running, while the components can be replaced without system shut-down.

The system in a preferred embodiment provides a high degree of fault tolerance and data integrity for applications that require very high system availability. Fault tolerance is achieved through a combination of redundant processors and memory along with dual I/O and mass storage systems (including mirrored disk volumes, for example), and redundant uninterruptable power supplies with redundant battery backup. Failure detection and methods for disabling and reintegrating modules permit continued operation without compromising data integrity during the presence of hardware faults.

Before a replacement module is reintegrated, the condition of the replacement may be verified by running a power-on self-test on that module and then performing module-dependent synchronization activities including: (1) for CPUs, the current state of the two good CPU modules is saved and all three modules are synchronized to begin executing the same instruction stream out of global memory, this instruction stream being a copy routine that reads the local memory contents of the two good CPUs to global memory and then writes the local memory data back to all three CPUs; (2) for memory modules, a replacement module is reintegrated by copying the contents of the good memory to local memory on the CPUs and recopying those contents back to both memory modules, this function being performed in block transfers and time shared with normal system processing, while any CPU or I/O processor writes that occur during the reintegration are also performed on both memory modules; (3) an I/O processor is reintegrated by initializing the I/O processor registers and interfaces on the new I/O processor, then reassigning I/O controllers to the replacement I/O processor; (4) reintegration of replacement I/O controllers involves powering up, assignment to an I/O processor, and reinitializing host and controller data structures; (5) reintegration of I/O devices involves device-specific activities performed by the operating system device drivers assigned to the I/O controller to which the device is attached (and possibly user level software).

The system can continue to function in the presence of multiple hardware faults as long as the following minimum configuration is maintained: (1) two of three CPUs; (2) one of two memory modules; (3) one of the I/O processors; (4) one of its disk subsystems; and (5) the appropriate power subsystem modules to support the above configuration.

A fault monitoring and detection system may be used for detecting corrupted data and automatically inhibiting permanent storage of corrupted data. A variety of fault detection mechanisms are used in the system including: (1) replicated operations (in CPU and memory areas) are voted to reduce number of checking circuits needed to ensure high data integrity; (2) error detecting codes may be used for data storage and transfer (includes parity, checksums on blocks of data, etc.); (3) checks on timing of communications between hardware modules (requests for service are monitored and timed and status reported); (4) self checking circuits are used; (5) soft errors are monitored and reported.

In accordance with one feature of the invention, a fault-tolerant computer system employs a power supply system including a battery backup so that upon AC power failure the system can execute an orderly shutdown, saving state to disk. A restart procedure restores the state existing at the time of power failure if the AC power has been restored by the time the shutdown is completed.

In accordance with another feature of the invention, a fault-tolerant computer system employs a pseudo-filesystem to dynamically manage the hardware components. A directory which appears as a standard, hierarchical directory in this filesystem contains a file for each component; each file maps to either a hardware component or a software module. The pseudo-filesystem hierarchy is determined during system initialization and is automatically updated whenever the software or hardware configuration changes. The hierarchical method of presentation provides a natural way of illustrating the connection between compo-

nents. An accurate map of the current state of the system can be viewed using standard tools for listing files. The pseudo-filesystem called /config filesystem herein, is implemented as a Unix filesystem in the Unix filesystem switch. Internally, /config files are grouped into a set of subsystems (e.g., subdirectories for software, CPUs, memory units, I/O processors, etc.). Each file is represented by an information node (inode) which stores information about the subsystem and component it represents. When a filesystem request to read, write or modify an inode is received the request is passed on to the corresponding subsystem. Return status from the subsystem is returned as status from the filesystem request. When the operating system detects a change in the system configuration (e.g., a failure of a component) the corresponding inodes in the /config filesystem are changed.

#### BRIEF DESCRIPTION OF THE DRAWINGS

The features believed characteristic of the invention are set forth in the appended claims. The invention itself, however, as well as other features and advantages thereof, may best be understood by reference to the detailed description of a specific embodiment which follows, when read in conjunction with the accompanying drawings, wherein:

Figure 1 is an electrical diagram in block form of a computer system according to one embodiment of the invention;

Figure 2 is an electrical schematic diagram in block form of one of the CPUs of the system of Figure 1;

Figure 3 is an electrical schematic diagram in block form of one of the microprocessor chips used in the CPU of Figure 2;

Figure 4 is an electrical schematic diagram in block form of one of the memory modules in the computer system of Figure 1;

Figure 5 is a timing diagram showing events occurring on the CPU to memory busses in the system of Figure 1;

Figure 6 is an electrical schematic diagram in block form of one of the I/O processors in the computer system of Figure 1;

Figure 7 is a timing diagram showing events vs. time for the transfer protocol between a memory module and an I/O processor in the system of Figure 1;

Figure 8 is an electrical schematic diagram in block form of the interrupt synchronization circuit used in the CPU of Figure 2;

Figure 9 is a physical memory map of the memories used in the system of Figures 1, 2, 3 and 4;

Figure 10 is a virtual memory map of the CPUs used in the system of Figures 1, 2, 3 and 4;

Figure 11 is a diagram of the format of the virtual address and the TLB entries in the microprocessor chips in the CPU according to Figure 2 or 3;

Figure 12, is an illustration of the private memory locations in the memory map of the global memory modules in the system of Figures 1, 2, 3 and 4;

Figure 13 is a schematic diagram in block form of the system of one embodiment of the invention including a fault-tolerant power supply;

Figure 14 is a flow chart showing the process of detecting an error, isolating the error to a faulty module and placing the module offline;

Figure 15 is a flow chart showing the system recovery process when a replacement module is installed;

Figure 16 is a timing diagram of events vs. time showing various events in the execution of a powerfail;

Figure 17 is a diagram of the tree structure of the /config filesystem according to one feature of the invention.

#### DETAILED DESCRIPTION OF SPECIFIC EMBODIMENT

With reference to Figure 1, a computer system using features of the invention is shown in one embodiment having three identical processors 11, 12 and 13, referred to as CPU-A, CPU-B and CPU-C, which operate as one logical processor, all three typically executing the same instruction stream; the only time the three processors are not executing the same instruction stream is in such operations as power-up self test, diagnostics and the like. The three processors are coupled to two memory modules 14 and 15, referred to as Memory-#1 and Memory-#2, each memory storing the same data in the same logical address space. In a preferred embodiment, each one of the processors 11, 12 and 13 contains its own local memory 16, as well, accessible only by the processor containing this memory. Figure 1 illustrates a computer system of one type that may employ features such as reintegration, power-fail and autorestart according to the invention. Of course, these features may as well be used in systems of a more general type without the

redundancy and the like, but will more likely find utility in fault-tolerant systems.

Each one of the processors 11, 12 and 13, as well as each one of the memory modules 14 and 15, has its own separate clock oscillator 17; in this embodiment, the processors are not run in "lock step", but instead are loosely synchronized, i.e., using events such as external memory references to bring the CPUs into synchronization. External interrupts are synchronized among the three CPUs by a technique employing a set of busses 18 for coupling the interrupt requests and status from each of the processors to the other two; each one of the processors CPU-A, CPU-B and CPU-C is responsive to the three interrupt requests, its own and the two received from the other CPUs, to present an interrupt to the CPUs at the same point in the execution stream. The memory modules 14 and 15 vote the memory references, and allow a memory reference to proceed only when all three CPUs have made the same request (with provision for faults). In this manner, the processors are synchronized at the time of external events (memory references), resulting in the processors typically executing the same instruction stream, in the same sequence, but not necessarily during aligned clock cycles in the time between synchronization events. In addition, external interrupts are synchronized to be executed at the same point in the instruction stream of each CPU.

The CPU-A processor 11 is connected to the Memory-#1 module 14 and to the Memory-#2 module 15 by a bus 21; likewise the CPU-B is connected to the modules 14 and 15 by a bus 22, and the CPU-C is connected to the memory modules by a bus 23. These busses 21, 22, 23 each include a 32-bit multiplexed address/data bus, a command bus, and control lines for address and data strobes. The CPUs have control of these busses 21, 22 and 23, so there is no arbitration, or bus-request and bus-grant.

Each one of the memory modules 14 and 15 is separately coupled to a respective input/output bus 24 or 25, and each of these busses is coupled to two (or more) input/output processors 26 and 27. The system can have multiple I/O processors as needed to accommodate the I/O devices needed for the particular system configuration. Each one of the input/output processors 26 and 27 is connected to a bus 28, and each bus 28 is connected to one or more bus interface modules 29 for interface with a standard I/O controller 30 which may be of the VMEbus<sup>TM</sup> type. Each bus interface module 29 is connected to two of the busses 28, so failure of one I/O processor 26 or 27, or failure of one of the bus channels 28, can be tolerated. The I/O processors 26 and 27 can be addressed by the CPUs 11, 12 and 13 through the memory modules 14 and 15, and can signal an interrupt to the CPUs via the memory modules. Disk drives, terminals with CRT screens and keyboards, and network adapters, are typical peripheral devices operated by the controllers 30. The controllers 30 may make DMA-type references to the memory modules 14 and 15 to transfer blocks of data. Each one of the I/O processors 26, 27, etc., has certain individual lines directly connected to each one of the memory modules for bus request, bus grant, etc.; these point-to-point connections are called "radials" and are included in a group of radial lines 31.

A system status bus 32 is individually connected to each one of the CPUs 11, 12 and 13, to each memory module 14 and 15, and to each of the I/O processors 26 and 27, for the purpose of providing information on the status of each element. This status bus provides information about which of the CPUs, memory modules and I/O processors is currently in the system and operating properly, and this information is maintained in the /config filesystem according to one feature of the invention.

An acknowledge/status bus 33 connecting the three CPUs and two memory modules includes individual lines by which the modules 14 and 15 send acknowledge signals to the CPUs when memory requests are made by the CPUs, and at the same time a status field is sent to report on the status of the command and whether it executed correctly. The memory modules not only check parity on data read from or written to the global memory, but also check parity on data passing through the memory modules to or from the I/O busses 24 and 25, as well as checking the validity of commands. It is through the status lines in bus 33 that these checks are reported to the CPUs 11, 12 and 13, so if errors occur a fault routine can be entered to isolate a faulty component.

Even though both memory modules 14 and 15 are storing the same data in global memory, and operating to perform every memory reference in duplicate, one of these memory modules is designated as primary and the other as back-up, at any given time. Memory write operations are executed by both memory modules so both are kept current, and also a memory read operation is executed by both, but only the primary module actually loads the read-data back onto the busses 21, 22 and 23, and only the primary memory module controls the arbitration for multi-master busses 24 and 25. To keep the primary and back-up modules executing the same operations, a bus 34 conveys control information from primary to back-up. Either module can assume the role of primary at boot-up, and the roles can switch during operation under software control; the roles can also switch when selected error conditions are detected by the CPUs or other error-responsive parts of the system.

Certain interrupts generated in the CPUs are also voted by the memory modules 14 and 15. When the CPUs encounter such an interrupt condition (and are not stalled), they signal an interrupt request to the

memory modules by individual lines in an interrupt bus 35, so the three interrupt requests from the three CPUs can be voted. When all interrupts have been voted, the memory modules each send a voted-interruptsignal to the three CPUs via bus 35. This voting of interrupts also functions to check on the operation of the CPUs. The three CPUs synch the voted interrupt CPU interrupt signal via the inter-CPU bus 18 and present the interrupt to the processors at a common point in the instruction stream. This interrupt synchronization is accomplished without stalling any of the CPUs.

#### CPU Module:

Referring now to Figure 2, one of the processors 11, 12 or 13 is shown in more detail. All three CPU modules are of the same construction in a preferred embodiment, so only CPU-A will be described here. In order to keep costs within a competitive range, and to provide ready access to already-developed software and operating systems, it is preferred to use a commercially-available microprocessor chip, and any one of a number of devices may be chosen. The RISC (reduced instruction set) architecture has some advantage in implementing the loose synchronization as will be described, but more-conventional CISC (complex instruction set) microprocessors such as Motorola 68030 devices or Intel 80386 devices (available in 20-Mhz and 25-Mhz speeds) could be used. High-speed 32-bit RISC microprocessor devices are available from several sources in three basic types; Motorola produces a device as part number 88000, MIPS Computer Systems, Inc. and others produce a chip set referred to as the MIPS type, and Sun Microsystems has announced a so-called SPARC™ type (scalable processor architecture). Cypress Semiconductor of San Jose, California, for example, manufactures a microprocessor referred to as part number CY7C601 prodding 20-MIPS (million instructions per second), clocked at 33-MHz, supporting the SPARC standard, and Fujitsu manufactures a CMOS RISC microprocessor, part number S-25, also supporting the SPARC standard.

The CPU board or module in the illustrative embodiment, used as an example, employs a microprocessor chip 40 which is in this case an R2000 device designed by MIPS Computer Systems, Inc., and also manufactured by Integrated Device Technology, Inc. The R2000 device is a 32-bit processor using RISC architecture to provide high performance, e.g., 12-MIPS at 16.67-Mhz clock rate. Higher-speed versions of this device may be used instead, such as the R3000 that provides 20-MIPS at 25-MHz clock rate. The processor 40 also has a co-processor used for memory management, including a translation lookaside buffer to cache translations of logical to physical addresses. The processor 40 is coupled to a local bus having a data bus 41, an address bus 42 and a control bus 43. Separate instruction and data cache memories 44 and 45 are coupled to this local bus. These caches are each of 64K-byte size, for example, and are accessed within a single clock cycle of the processor 40. A numeric or floating point co-processor 46 is coupled to the local bus if additional performance is needed for these types of calculations; this numeric processor device is also commercially available from MIPS Computer Systems as part number R2010. The local bus 41,42,43, is coupled to an internal bus structure through a write buffer 50 and a read buffer 51. The write buffer is a commercially available device, part number R2020, and functions to allow the processor 40 to continue to execute Run cycles after storing data and address in the write buffer 50 for a write operation, rather than having to execute stall cycles while the write is completing.

In addition to the path through the write buffer 50, a path is provided to allow the processor 40 to execute write operations bypassing the write buffer 50. This path is a write buffer bypass 52 allows the processor, under software selection, to perform synchronous writes. If the write buffer bypass 52 is enabled (write buffer 50 not enabled) and the processor executes a write then the processor will stall until the write completes. In contrast, when writes are executed with the write buffer bypass 52 disabled the processor will not stall because data is written into the write buffer 50 (unless the write buffer is full). If the write buffer 50 is enabled when the processor 40 performs a write operation, the write buffer 50 captures the output data from bus 41 and the address from bus 42, as well as controls from bus 43. The write buffer 50 can hold up to four such data-address sets while it waits to pass the data on to the main memory. The write buffer runs synchronously with the clock 17 of the processor chip 40, so the processor-to-buffer transfers are synchronous and at the machine cycle rate of the processor. The write buffer 50 signals the processor if it is full and unable to accept data. Read operations by the processor 40 are checked against the addresses contained in the four-deep write buffer 50, so if a read is attempted to one of the data words waiting in the write buffer to be written to memory 16 or to global memory, the read is stalled until the write is completed.

The write and read buffers 50 and 51 are coupled to an internal bus structure having a data bus 53, an address bus 54 and a control bus 55. The local memory 16 is accessed by this internal bus, and a bus interface 56 coupled to the internal bus is used to access the system bus 21 (or bus 22 or 23 for the other CPUs). The separate data and address busses 53 and 54 of the internal bus (as derived from busses 41 and 42 of the local bus) are converted to a multiplexed address/data bus 57 in the system bus 21, and the



command and control lines are correspondingly converted to command lines 58 and control lines 59 in this external bus.

The bus interface unit 56 also receives the acknowledge/status lines 33 from the memory modules 14 and 15. In these lines 33, separate status lines 33-1 or 33-2 are coupled from each of the modules 14 and 15, so the responses from both memory modules can be evaluated upon the event of a transfer (read or write) between CPUs and global memory, as will be explained.

The local memory 16, in one embodiment, comprises about 8-Mbyte of RAM which can be accessed in about three or four of the machine cycles of processor 40, and this access is synchronous with the clock 17 of this CPU, whereas the memory access time to the modules 14 and 15 is much greater than that to local memory, and this access to the memory modules 14 and 15 is asynchronous and subject to the synchronization overhead imposed by waiting for all CPUs to make the request then voting. For comparison, access to a typical commercially-available disk memory through the I/O processors 26, 27 and 29 is measured in milliseconds, i.e., considerably slower than access to the modules 14 and 15. Thus, there is a hierarchy of memory access by the CPU chip 40, the highest being the instruction and data caches 44 and 45 which will provide a hit ratio of perhaps 95% when using 64-KByte cache size and suitable fill algorithms. The second highest is the local memory 16, and again by employing contemporary virtual memory management algorithms a hit ratio of perhaps 95% is obtained for memory references for which a cache miss occurs but a hit in local memory 16 is found, in an example where the size of the local memory is about 8-MByte. The net result, from the standpoint of the processor chip 40, is that perhaps greater than 99% of memory references (but not I/O references) will be synchronous and will occur in either the same machine cycle or in three or four machine cycles.

The local memory 16 is accessed from the internal bus by a memory controller 60 which receives the addresses from address bus 54, and the address strobes from the control bus 55, and generates separate row and column addresses, and RAS and CAS controls, for example, if the local memory 16 employs DRAMs with multiplexed addressing, as is usually the case. Data is written to or read from the local memory via data bus 53. In addition, several local registers 61, as well as non-volatile memory 62 such as NVRAMs, and high-speed PROMs 63, as may be used by the operating system, are accessed by the internal bus; some of this part of the memory is used only at power-on, some is used by the operating system and may be almost continuously within the cache 44, and other may be within the non-cached part of the memory map.

External interrupts are applied to the processor 40 by one of the pins of the control bus 43 or 55 from an interrupt circuit 65 in the CPU module of Figure 2. This type of interrupt is voted in the circuit 65, so that before an interrupt is executed by the processor 40 it is determined whether or not all three CPUs are presented with the interrupt; to this end, the circuit 65 receives interrupt pending inputs 66 from the other two CPUs 12 and 13, and sends an interrupt pending signal to the other two CPUs via line 67, these lines being part of the bus 18 connecting the three CPUs 11, 12 and 13 together. Also, for voting other types of interrupts, specifically CPU-generated interrupts, the circuit 65 can send an interrupt request from this CPU to both of the memory modules 14 and 15 by a line 68 in the bus 35, then receive separate voted-interrupt signals from the memory modules via lines 69 and 70; both memory modules will present the external interrupt to be acted upon. An interrupt generated in some external source such as a keyboard or disk drive on one of the I/O channels 28, for example, will not be presented to the interrupt pin of the chip 40 from the circuit 65 until each one of the CPUs 11, 12 and 13 is at the same point in the instruction stream, as will be explained.

Since the processors 40 are clocked by separate clock oscillators 17, there must be some mechanism for periodically bringing the processors 40 back into synchronization. Even though the clock oscillators 17 are of the same nominal frequency, e.g., 16.67-MHz, and the tolerance for these devices is about 25-ppm (parts per million), the processors can potentially become many cycles out of phase unless periodically brought back into synch. Of course, every time an external interrupt occurs the CPUs will be brought into synch in the sense of being interrupted at the same point in their instruction stream (due to the interrupt synch mechanism), but this does not help bring the cycle count into synch. The mechanism of voting memory references in the memory modules 14 and 15 will bring the CPUs into synch (in real time), as will be explained. However, some conditions result in long periods where no memory reference occurs, and so an additional mechanism is used to introduce stall cycles to bring the processors 40 back into synch. A cycle counter 71 is coupled to the clock 17 and the control pins of the processor 40 via control bus 43 to count machine cycles which are Run cycles (but not Stall cycles). This counter 71 includes a count register having a maximum count value selected to represent the period during which the maximum allowable drift between CPUs would occur (taking into account the specified tolerance for the crystal oscillators); when this count register overflows action is initiated to stall the faster processors until the slower processor or

processors catch up. This counter 71 is reset whenever a synchronization is done by a memory reference to the memory modules 14 and 15. Also, a refresh counter 72 is employed to perform refresh cycles on the local memory 16, as will be explained. In addition, a counter 73 counts machine cycle which are Run cycles but not Stall cycles, like the counter 71 does, but this counter 73 is not reset by a memory reference; the counter 73 is used for interrupt synchronization as explained below, and to this end produces the output signals CC-4 and CC-8 to the interrupt synchronization circuit 65.

The processor 40 has a RISC instruction set which does not support memory-to-memory instructions, but instead only memory-to-register or register-to-memory instructions (i.e., load or store). It is important to keep frequently-used data and the currently-executing code in local memory. Accordingly, a block-transfer operation is provided by a DMA state machine 74 coupled to the bus interface 56. The processor 40 writes a word to a register in the DMA circuit 74 to function as a command, and writes the starting address and length of the block to registers in this circuit 74. In one embodiment, the microprocessor stalls while the DMA circuit takes over and executes the block transfer, producing the necessary addresses, commands and strobes on the busses 53-55 and 21. The command executed by the processor 40 to initiate this block transfer can be a read from a register in the DMA circuit 74. Since memory management in the Unix operating system relies upon demand paging, these block transfers will most often be pages being moved between global and local memory and I/O traffic. A page is 4-KBytes. Of course, the busses 21, 22 and 23 support single-word read and write transfers between CPUs and global memory; the block transfers referred to are only possible between local and global memory.

#### The Processor:

Referring now to Figure 3, the R2000 or R3000 type of microprocessor 40 of the example embodiment is shown in more detail. This device includes a main 32-bit CPU 75 containing thirty-two 32-bit general purpose registers 76, a 32-bit ALU 77, a zero-to-64 bit shifter 78, and a 32-by-32 multiply/divide circuit 79. This CPU also has a program counter 80 along with associated incrementer and adder. These components are coupled to a processor bus structure 81, which is coupled to the local data bus 41 and to an instruction decoder 82 with associated control logic to execute instructions fetched via data bus 41. The 32-bit local address bus 42 is driven by a virtual memory management arrangement including a translation lookaside buffer (TLB) 83 within an on-chip memory-management coprocessor. The TLB 83 contains sixty-four entries to be compared with a virtual address received from the microprocessor block 75 via virtual address bus 84. The low-order 16-bit part 85 of the bus 42 is driven by the low-order part of this virtual address bus 84, and the high-order part is from the bus 84 if the virtual address is used as the physical address, or is the tag entry from the TLB 83 via output 86 if virtual addressing is used and a hit occurs. The control lines 43 of the local bus are connected to pipeline and bus control circuitry 87, driven from the internal bus structure 81 and the control logic 82.

The microprocessor block 75 in the processor 40 is of the RISC type in that most instructions execute in one machine cycle, and the instruction set uses register-to-register and load/store instructions rather than having complex instructions involving memory references along with ALU operations. The main CPU 75 is highly pipelined to facilitate the goal of averaging one instruction execution per machine cycle. A single instruction is executed over a period including five machine cycles, where a machine cycle is one clock period or 60-nsec for a 16.67-MHz clock 17. Construction and operation of the R2000 processor is disclosed in Kane, "MIPS R2000 RISC Architecture", Prentice Hall, 1987.

#### Memory Module:

With reference to Figure 4, one of the memory modules 14 or 15 is shown in detail. Both memory modules are of the same construction in a preferred embodiment, so only the Memory#1 module is shown. The memory module includes three input/output ports 91, 92 and 93 coupled to the three busses 21, 22 and 23 coming from the CPUs 11, 12 and 13, respectively. Inputs to these ports are latched into registers 94, 95 and 96 each of which has separate sections to store data, address, command and strobes for a write operation, or address, command and strobes for a read operation. The contents of these three registers are voted by a vote circuit 100 having inputs connected to all sections of all three registers. If all three of the CPUs 11, 12 and 13 make the same memory request (same address, same command), as should be the case since the CPUs are typically executing the same instruction stream, then the memory request is allowed to complete; however, as soon as the first memory request is latched into any one of the three latches 94, 95 or 96, it is passed on immediately to begin the memory access. To this end, the address, data and command are applied to an internal bus including data bus 101, address bus 102 and control bus

103. From this internal bus the memory request accesses various resources, depending upon the address, and depending upon the system configuration.

In one embodiment, a large DRAM 104 is accessed by the internal bus, using a memory controller 105 which accepts the address from address bus 102 and memory request and strobes from control bus 103 to generate multiplexed row and column addresses for the DRAM so that data input/output is provided on the data bus 101. This DRAM 104 is also referred to as global memory, and is of a size of perhaps 32-MByte in one embodiment. In addition, the internal bus 101-103 can access control and status registers 106, a quantity of non-volatile RAM 107, and write-protect RAM 108. The memory reference by the CPUs can also bypass the memory in the memory module 14 or 15 and access the I/O busses 24 and 25 by a bus interface 109 which has inputs connected to the internal bus 101-103. If the memory module is the primary memory module, a bus arbitrator 110 in each memory module controls the bus interface 109. If a memory module is the backup module, the bus 34 controls the bus interface 109.

A memory access to the DRAM 104 is initiated as soon as the first request is latched into one of the latches 94, 95 or 96, but is not allowed to complete unless the vote circuit 100 determines that a plurality of the requests are the same, with provision for faults. The arrival of the first of the three requests causes the access to the DRAM 104 to begin. For a read, the DRAM 104 is addressed, the sense amplifiers are strobed, and the data output is produced at the DRAM outputs, so if the vote is good after the third request is received then the requested data is ready for immediate transfer back to the CPUs. In this manner, voting is overlapped with DRAM access.

Referring to Figure 5, the busses 21, 22 and 23 apply memory requests to ports 91, 92 and 93 of the memory modules 14 and 15 in the format illustrated. Each of these busses consists of thirty-two bidirectional multiplexed address/data lines, thirteen unidirectional command lines, and two strobes. The command lines include a field which specifies the type of bus activity, such as read, write, block transfer, single transfer, I/O read or write, etc. Also, a field functions as a byte enable for the four bytes. The strobes are AS, address strobe, and DS, data strobe. The CPUs 11, 12 and 13 each control their own bus 21, 22 or 23; in this embodiment, these are not multi-master busses; there is no contention or arbitration. For a write, the CPU drives the address and command onto the bus in one cycle along with the address strobe AS (active low), then in a subsequent cycle (possibly the next cycle, but not necessarily) drives the data onto the address/data lines of the bus at the same time as a data strobe DS. The address strobe AS from each CPU causes the address and command then appearing at the ports 91, 92 or 93 to be latched into the address and command sections of the registers 94, 95 and 96, as these strobes appear, then the data strobe DS causes the data to be latched. When a plurality (two out of three in this embodiment) of the busses 21, 22 and 23 drive the same memory request into the latches 94, 95 and 96, the vote circuit 100 passes on the final command to the bus 103 and the memory access will be executed; if the command is a write, an acknowledge ACK signal is sent back to each CPU by a line 112 (specifically line 112-1 for Memory#1 and line 112-2 for Memory#2) as soon as the write has been executed, and at the same time status bits are driven via acknowledge/status bus 33 (specifically lines 33-1 for Memory#1 and lines 33-2 for Memory#2) to each CPU at time T3 of Figure 5. The delay T4 between the last strobe DS (or AS if a read) and the ACK at T3 is variable, depending upon how many cycles out of synch the CPUs are at the time of the memory request, and depending upon the delay in the voting circuit and the phase of the internal independent clock 17 of the memory module 14 or 15 compared to the CPU clocks 17. If the memory request issued by the CPUs is a read, then the ACK signal on lines 112-1 and 112-2 and the status bits on lines 33-1 and 33-2 will be sent at the same time as the data is driven to the address/data bus, during time T3; this will release the stall in the CPUs and thus synchronize the CPU chips 40 on the same instruction. That is, the fastest CPU will have executed more stall cycles as it waited for the slower ones to catch up, then all three will be released at the same time, although the clocks 17 will probably be out of phase; the first instruction executed by all three CPUs when they come out of stall will be the same instruction.

All data being sent from the memory module 14 or 15 to the CPUs 11, 12 and 13, whether the data is read data from the DRAM 104 or from the memory locations 106-108, or is I/O data from the busses 24 and 25, goes through a register 114. This register is loaded from the internal data bus 101, and an output 115 from this register is applied to the address/data lines for busses 21, 22 and 23 at ports 91, 92 and 93 at time T3. Parity is checked when the data is loaded to this register 114. All data written to the DRAM 104, and all data on the I/O busses, has parity bits associated with it, but the parity bits are not transferred on busses 21, 22 and 23 to the CPU modules. Parity errors detected at the read register 114 are reported to the CPU via the status busses 33-1 and 33-2. Only the memory module 14 or 15 designated as primary will drive the data in its register 114 onto the busses 21, 22 and 23. The memory module designated as backup or secondary will complete a read operation all the way up to the point of loading the register 114 and checking parity, and will report status on buses 33-1 and 33-2, but no data will be driven to the busses 21,

22 and 23.

A controller 117 in each memory module 14 or 15 operates as a state machine clocked by the clock oscillator 17 for this module and receiving the various command lines from bus 103 and busses 21-23, etc., to generate control bits to load registers and busses, generate external control signals, and the like. This controller also is connected to the bus 34 between the memory modules 14 and 15 which transfers status and control information between the two. The controller 117 in the module 14 or 15 currently designated as primary will arbitrate via arbitrator 110 between the I/O side (interface 109) and the CPU side (ports 91-93) for access to the common bus 101-103. This decision made by the controller 117 in the primary memory module 14 or 15 is communicated to the controller 117 of other memory module by the lines 34, and forces the other memory module to execute the same access.

The controller 117 in each memory module also introduces refresh cycles for the DRAM 104, based upon a refresh counter 118 receiving pulses from the clock oscillator 17 for this module. The DRAM must receive 512 refresh cycles every 8-msec, so on average there must be a refresh cycle introduced about every 15-microsec. The counter 118 thus produces an overflow signal to the controller 117 every 15-microsec., and if an idle condition exists (no CPU access or I/O access executing) a refresh cycle is implemented by a command applied to the bus 103. If an operation is in progress, the refresh is executed when the current operation is finished. For lengthy operations such as block transfers used in memory paging, several refresh cycles may be backed up and execute in a burst mode after the transfer is completed; to this end, the number of overflows of counter 118 since the last refresh cycle are accumulated in a register associated with the counter 118.

Interrupt requests for CPU-generated interrupts are received from each CPU 11, 12 and 13 individually by lines 68 in the interrupt bus 35; these interrupt requests are sent to each memory module 14 and 15. These interrupt request lines 68 in bus 35 are applied to an interrupt vote circuit 119 which compares the three requests and produces a voted interrupt signal on outgoing line 69 of the bus 35. The CPUs each receive a voted interrupt signal on the two lines 69 and 70 (one from each module 14 and 15) via the bus 35. The voted interrupts from each memory module 14 and 15 are ORed and presented to the interrupt synchronizing circuit 65. The CPUs, under software control, decide which interrupts to service. External interrupts, generated in the I/O processors or I/O controllers, are also signalled to the CPUs through the memory modules 14 and 15 via lines 69 and 70 in bus 35, and likewise the CPUs only respond to an interrupt from the primary module 14 or 15.

#### I/O Processor:

Referring now to Figure 6, one of the I/O processors 26 or 27 is shown in detail. The I/O processor has two identical ports, one port 121 to the I/O bus 24 and the other port 122 to the I/O bus 25. Each one of the I/O busses 24 and 25 consists of: a 36-bit bidirectional multiplexed address/data bus 123 (containing 32-bits plus 4-bits parity), a bidirectional command bus 124 defining the read, write, block read, block write, etc., type of operation that is being executed, an address line that designates which location is being addressed, either internal to I/O processor or on busses 28, and the byte mask, and finally control lines 125 including address strobe, data strobe, address acknowledge and data acknowledge. The radial lines in bus 31 include individual lines from each I/O processor to each memory module: bus request from I/O processor to the memory modules, bus grant from the memory modules to the I/O processor, interrupt request lines from I/O processor to memory module, and a reset line from memory to I/O processor. Lines to indicate which memory module is primary are connected to each I/O processor via the system status bus 32. A controller or state machine 126 in the I/O processor of Figure 6 receives the command, control, status and radial lines and internal data, and command lines from the busses 28, and defines the internal operation of the I/O processor, including operation of latches 127 and 128 which receive the contents of busses 24 and 25 and also hold information for transmitting onto the busses.

Transfer on the busses 24 and 25 from memory module to I/O processor uses a protocol as shown in Figure 7 with the address and data separately acknowledged. The arbitrator circuit 110 in the memory module which is designated primary performs the arbitration for ownership of the I/O busses 24 and 25. When a transfer from CPUs to I/O is needed, the CPU request is presented to the arbitration logic 110 in the memory module. When the arbiter 110 grants this request the memory modules apply the address and command to busses 123 and 124 (of both busses 24 and 25) at the same time the address strobe is asserted on bus 125 (of both busses 24 and 25) in time T1 of Figure 7; when the controller 126 has caused the address to be latched into latches 127 or 128, the address acknowledge is asserted on bus 125, then the memory modules place the data (via both busses 24 and 25) on the bus 123 and a data strobe on lines 125 in time T2, following which the controller causes the data to be latched into both latches 127 and 128

and a data acknowledge signal is placed upon the lines 125, so upon receipt of the data acknowledge, both of the memory modules release the bus 24, 25 by de-asserting the address strobe signal. The I/O processor then deasserts the address acknowledge signal.

For transfers from I/O processor to the memory module, when the I/O processor needs to use the I/O bus, it asserts a bus request by a line in the radial bus 31, to both busses 24 and 25, then waits for a bus grant signal from an arbitrator circuit 110 in the primary memory module 14 or 15, the bus grant line also being one of the radials. When the bus grant has been asserted, the controller 126 then waits until the address strobe and address acknowledge signals on busses 125 are deasserted (i.e., false) meaning the previous transfer is completed. At that time, the controller 126 causes the address to be applied from latches 127 and 128 to lines 123 of both busses 24 and 25, the command to be applied to lines 124, and the address strobe to be applied to the bus 125 of both busses 24 and 25. When address acknowledge is received from both busses 24 and 25, these are followed by applying the data to the address/data busses, along with data strobes, and the transfer is completed with a data acknowledge signals from the memory modules to the I/O processor.

The latches 127 and 128 are coupled to an internal bus 129 including an address bus 129a, and data bus 129b and a control bus 129c, which can address internal status and control registers 130 used to set up the commands to be executed by the controller state machine 126, to hold the status distributed by the bus 32, etc. These registers 130 are addressable for read or write from the CPUs in the address space of the CPUs. A bus interface 131 communicates with the bus 28, under control of the controller 126. The bus 28 includes an address bus 28a, a data bus 28b, a control bus 28c, and radials 28d, and all of these lines are communicated through the bus interface modules 29 to the I/O controllers 30; the bus interface module 29 contains a multiplexer 132 to allow only one set of bus lines 28 (from one I/O processor or the other but not both) drive the controller 30. Internal to the controller 30 are command, control, status and data registers 133 which (as is standard practice for peripheral controllers of this type) are addressable from the CPUs 11, 12 and 13 for read and write to initiate and control operations in I/O devices.

Each one of the I/O controllers 30 on the busses 28 has connections via a multiplexer 132 in the BIM 29 to both I/O processors 26 and 27 and can be controlled by either one, but is bound to one or the other by the program executing in the CPUs. In the event of a failure in one of the I/O processors, an I/O controller can be reassigned to the remaining I/O processor via the second port on BIM 29. A particular address (or set of addresses) is established for control and data-transfer registers 133 representing each controller 30, and these addresses are maintained in an I/O page table (normally in the kernel data section of local memory) by the operating system. These addresses associate each controller 30 as being accessible only through either I/O processor #1 or #2, but not both. That is, a different address is used to reach a particular register 133 via I/O processor 26 compared to I/O processor 27. The bus interface 131 (and controller 126) can switch the multiplexer 132 to accept bus 28 from one or the other, and this is done by a write to the registers 130 of the I/O processors from the CPUs. Thus, when the device driver is called up to access this controller 30, the operating system uses these addresses in the page table to do it. The processors 40 access the controllers 30 by I/O writes to the control and data-transfer registers 133 in these controllers using the write buffer bypass path 52, rather than through the write buffer 50, so these are synchronous writes, voted by circuits 100, passed through the memory modules to the busses 24 or 25, thus to the selected bus 28; the processors 40 stall until the write is completed. The I/O processor board of Figure 6 is configured to detect certain failures, such as improper commands, time-outs where no response is received over bus 28, parity-checked data, etc., and when one of these failures is detected the I/O processor reports the error to the CPU via both memory modules 14 and 15 via busses 24 and 25. The CPU terminates the stall and continues processing. This is detected by the bus interface 56 as a bus fault, resulting in an interrupt as will be explained, and self-correcting action if possible.

#### Synchronization:

The processors 40 used in the illustrative embodiment are of pipelined architecture with overlapped instruction execution, as discussed above. A synchronization technique used in this embodiment relies upon cycle counting, i.e., incrementing a counter 71 and a counter 73 of Figure 2 every time an instruction is executed. Every time the pipeline advances an instruction is executed. One of the control lines in the control bus 43 is a signal RUN# which indicates that the pipeline is stalled; when RUN# is high the pipeline is stalled, when RUN# is low (logic zero) the pipeline advances each machine cycle. This RUN# signal is used in the numeric processor 46 to monitor the pipeline of the processor 40 so this coprocessor 46 can run in lockstep with its associated processor 40. This RUN# signal in the control bus 43 along with the clock 17 are used by the counters 71 and 73 to count Run cycles.

The size of the counter register 71, in a preferred embodiment, is chosen to be 4096, i.e.,  $2^{12}$ , which is selected because the tolerances of the crystal oscillators used in the clocks 17 are such that the drift in about 4K Run cycles on average results in a skew or difference in number of cycles run by a processor chip 40 of about all that can be reasonably allowed for proper operation of the interrupt synchronization.

5 One synchronization mechanism is to force action to cause the CPUs to synchronize whenever the counter 71 overflows. One such action is to force a cache miss in response to an overflow signal OVFL from the counter 71; this can be done by merely generating a false Miss signal (e.g., TagValid bit not set) on control bus 43 for the next I-cache reference, thus forcing a cache miss exception routine to be entered and the resultant memory reference will produce synchronization just as any memory reference does. Another

10 method of forcing synchronization upon overflow of counter 71 is by forcing a stall in the processor 40, which can be done by using the overflow signal OVFL to generate a CP Busy (coprocessor busy) signal on control bus 43 via logic circuit 71a of Figure 2; this CP Busy signal always results in the processor 40 entering stall until CP Busy is deasserted. All three processors will enter this stall because they are executing the same code and will count the same cycles in their counter 71, but the actual time they enter

15 the stall will vary; the logic circuit 71a receives the RUN# signal from bus 43 of the other two processors via input R#, so when all three have stalled the CP Busy signal is released and the processors will come out of stall in synch again.

Thus, two synchronization techniques have been described, the first being the synchronization resulting from voting the memory references in circuits 100 in the memory modules, and the second by the overflow of counter 71 as just set forth. In addition, interrupts are synchronized, as will be described below. It is important to note, however, that the processors 40 are basically running free at their own clock speed, and are substantially decoupled from one another, except when synchronizing events occur. The fact that pipelined microprocessors are used would make lock-step synchronization with a single clock more difficult, and would degrade performance; also, use of the write buffer 50 serves to decouple the processors, and

25 would be much less effective with close coupling of the processors. Likewise, the high-performance resulting from using instruction and data caches, and virtual memory management with the TLBs 83, would be more difficult to implement if close coupling were used, and performance would suffer.

#### Interrupt Synchronization:

30 The interrupt synchronization technique must distinguish between real time and so-called "virtual time". Real time is the external actual time, clock-on-the-wall time, measured in seconds, or for convenience, measured in machine cycles which are 60-nsec divisions in the example. The clock generators 17 each produce clock pulses in real time, of course. Virtual time is the internal cycle-count time of each of the

35 processor chips 40 as measured in each one of the cycle counters 71 and 73, i.e., the instruction number of the instruction being executed by the processor chip, measured in instructions since some arbitrary beginning point.

The three CPUs of the system of Figures 1 -3 are required to function as a single logical processor, thus requiring that the CPUs adhere to certain restrictions regarding their internal state to ensure that the

40 programming model of the three CPUs is that of a single logical processor. Except in failure modes and in diagnostic functions, the instruction streams of the three CPUs are required to be identical. If not identical, then voting global memory accesses at voting circuitry 100 of Figure 4 would be difficult; the voter would not know whether one CPU was faulty or whether it was executing a different sequence of instructions. The synchronization scheme is designed so that if the code stream of any CPU diverges from the code stream of the other CPUs, then a failure is assumed to have occurred. Interrupt synchronization provides one of the

45 mechanisms of maintaining a single CPU image.

All interrupts are required to occur synchronous to virtual time, ensuring that the instruction streams of the three processors CPU-A, CPU-B and CPU-C will not diverge as a result of interrupts (there are other causes of divergent instruction streams, such as one processor reading different data than the data read by

50 the other processors). Several scenarios exist whereby interrupts occurring asynchronous to virtual time would cause the code streams to diverge. For example, an interrupt causing a context switch on one CPU before process A completes, but causing the context switch after process A completes on another CPU would result in a situation where, at some point later, one CPU continues executing process A, but the other CPU cannot execute process A because that process had already completed. If in this case the interrupts

55 occurred asynchronous to virtual time, then just the fact that the exception program counters were different could cause problems. The act of writing the exception program counters to global memory would result in the voter detecting different data from the three CPUs, producing a vote fault.

Certain types of exceptions in the CPUs are inherently synchronous to virtual time. One example is a

breakpoint exception caused by the execution of a breakpoint instruction. Since the instruction streams of the CPUs are identical, the breakpoint exception occurs at the same point in virtual time on all three of the CPUs. Similarly, all such internal exceptions inherently occur synchronous to virtual time. For example, TLB exceptions are internal exceptions that are inherently synchronous. TLB exceptions occur because the virtual page number does not match any of the entries in the TLB 83. Because the act of translating addresses is solely a function of the instruction stream (exactly as in the case of the breakpoint exception), the translation is inherently synchronous to virtual time. In order to ensure that TLB exceptions are synchronous to virtual time, the state of the TLBs 83 must be identical in all three of the CPUs 11, 12 and 13, and this is guaranteed because the TLB 83 can only be modified by software. Again, since all of the CPUs execute the same instruction stream, the state of the TLBs 83 are always changed synchronous to virtual time. So, as a general rule of thumb, if an action is performed by software then the action is synchronous to virtual time. If an action is performed by hardware, which does not use the cycle counters 71, then the action is generally synchronous to real time.

External exceptions are not inherently synchronous to virtual time. I/O devices 26, 27 or 30 have no information about the virtual time of the three CPUs 11, 12 and 13. Therefore, all interrupts that are generated by these I/O devices must be synchronized to virtual time before presenting to the CPUs, as explained below. Floating point exceptions are different from I/O device interrupts because the floating point coprocessor 46 is tightly coupled to the microprocessor 40 within the CPU.

External devices view the three CPUs as one logical processor, and have no information about the synchronicity or lack of synchronicity between the CPUs, so the external devices cannot produce interrupts that are synchronous with the individual instruction stream (virtual time) of each CPU. Without any sort of synchronization, if some external device drove an interrupt at some instant of real time, and the interrupt was presented directly to the CPUs at this time then the three CPUs would take an exception trap at different instructions, resulting in an unacceptable state of the three CPUs. This is an example of an event (assertion of an interrupt) which is synchronous to real time but not synchronous to virtual time.

Interrupts are synchronized to virtual time in the system of Figures 1-3 by performing a distributed vote on the interrupts and then presenting the interrupt to the processor on a predetermined cycle count. Figure 8 shows a more detailed block diagram of the interrupt synchronization logic 65 of Figure 2. Each CPU contains a distributor 135 which captures the external interrupt from the line 69 or 70 coming from the modules 14 or 15; this capture occurs on a predetermined cycle count, e.g., at count-4 as signalled on an input line CC-4 from the counter 71. The captured interrupt is distributed to the other two CPUs via the inter-CPU bus 18. These distributed interrupts are called pending interrupts. There are three pending interrupts, one from each CPU 11, 12 and 13. A voter circuit 136 captures the pending interrupts and performs a vote to verify that all of the CPUs did receive the external interrupt request. On a predetermined cycle count (detected from the cycle counter 71), in this example cycle-8 received by input line CC-8, the interrupt voter 136 presents the interrupt to the interrupt pin on its respective microprocessor 40 via line 137 and control bus 55 and 43. Since the cycle count that is used to present the interrupt is predetermined, all of the microprocessors 40 will receive the interrupt on the same cycle count and thus the interrupt will have been synchronized to virtual time.

#### Memory Management:

The CPUs 11, 12 and 13 of Figures 1-3 have memory space organized as illustrated in Figure 9. Using the example that the local memory 16 is 8-MByte and the global memory 14 or 15 is 32-MByte, note that the local memory 16 is part of the same continuous zero-to-40M map of CPU memory access space, rather than being a cache or a separate memory space; realizing that the 0-8M section is triplicated (in the three CPU modules), and the 8-40M section is duplicated, nevertheless logically there is merely a single 0-40M physical address space. An address over 8-MByte on bus 54 causes the bus interface 56 to make a request to the memory modules 14 and 15, but an address under 8-MByte will access the local memory 16 within the CPU module itself. Performance is improved by placing more of the memory used by the applications being executed in local memory 16, and so as memory chips are available in higher densities at lower cost and higher speeds, additional local memory will be added, as well as additional global memory. For example, the local memory might be 32-MByte and the global memory 128-MByte. On the other hand, if a very minimum-cost system is needed, and performance is not a major determining factor, the system can be operated with no local memory, all main memory being in the global memory area (in memory modules 14 and 15), although the performance penalty is high for such a configuration.

The content of local memory portion 141 of the map of Figure 9 is identical in the three CPUs 11, 12 and 13. Likewise, the two memory modules 14 and 15 contain identically the same data in their space 142

at any given instant. Within the local memory portion 141 is stored the kernel 143 (code) for the Unix operating system, and this area is physically mapped within a fixed portion of the local memory 16 of each CPU. Likewise, kernel data is assigned a fixed area 144 in each local memory 16; except upon boot-up, these blocks do not get swapped to or from global memory or disk. Another portion 145 of local memory 16 is employed for user program (and data) pages, which are swapped to area 146 of the global memory 14 and 15 under control of the operating system. The global memory area 142 is used as a staging area for user pages in area 148, and also as a disk buffer in an area 147; if the CPUs are executing code which performs a write of a block of data or code from local memory 16 to disk 148, then the sequence is to always write to a disk buffer area 147 instead because the time to copy to area 147 is negligible compared to the time to copy directly to the I/O processor 26 and 27 and thus via I/O controller 30 to disk 148. Then, while the CPUs proceed to execute other code, the write-to-disk operation is done, transparent to the CPUs, to move the block from area 147 to disk 148. In a like manner, the global memory area 146 is mapped to include an I/O staging 149 area, for similar treatment of I/O accesses other than disk (e.g., video).

The physical memory map of Figure 9 is correlated with the virtual memory management system of the processor 40 in each CPU. Figure 10 illustrates the virtual address map of the R2000 processor chip used in the example embodiment, although it is understood that other microprocessor chips supporting virtual memory management with paging and a protection mechanism would provide corresponding features.

In Figure 10, two separate 2-GByte virtual address spaces 150 and 151 are illustrated; the processor 40 operates in one of two modes, user mode and kernel mode. The processor can only access the area 150 in the user mode, or can access both the areas 150 and 151 in the kernel mode. The kernel mode is analogous to the supervisory mode provided in many machines. The processor 40 is configured to operate normally in the user mode until an exception is detected forcing it into the kernel mode, where it remains until a restore from exception (RFE) instruction is executed. The manner in which the memory addresses are translated or mapped depends upon the operating mode of the microprocessor, which is defined by a bit in a status register. When in the user mode, a single, uniform virtual address space 150 referred to as "kuseg" of 2-GByte size is available. Each virtual address is also extended with a 6-bit process identifier (PID) field to form unique virtual addresses for up to sixty-four user processes. All references to this segment 150 in user mode are mapped through the TLB 83, and use of the caches 144 and 145 is determined by bit settings for each page entry in the TLB entries; i.e., some pages may be cachable and some not as specified by the programmer.

When in the kernel mode, the virtual address space includes both the areas 150 and 151 of Figure 10, and this space has four separate segments kuseg 150, kseg0 152, kseg1 153 and kseg2 154. The kuseg 150 segment for the kernel mode is 2-GByte in size, coincident with the "kuseg" of the user mode, so when in the kernel mode the processor treats references to this segment just like user mode references, thus streamlining kernel access to user data. The kuseg 150 is used to hold user code and data, but the operating system often needs to reference this same code or data. The kseg0 area 152 is a 512-MByte kernel physical address space direct-mapped onto the first 512-MBytes of physical address space, and is cached but does not use the TLB 83; this segment is used for kernel executable code and some kernel data, and is represented by the area 143 of Figure 9 in local memory 16. The kseg1 area 153 is also directly mapped into the first 512-MByte of physical address space, the same as kseg0, and is uncached and uses no TLB entries. Kseg1 differs from kseg0 only in that it is uncached. Kseg1 is used by the operating system for I/O registers, ROM code and disk buffers, and so corresponds to areas 147 and 149 of the physical map of Figure 9. The kseg2 area 154 is a 1-GByte space which, like kuseg, uses TLB 83 entries to map virtual addresses to arbitrary physical ones, with or without caching. This kseg2 area differs from the kuseg area 150 only in that it is not accessible in the user mode, but instead only in the kernel mode. The operating system uses kseg2 for stacks and per-process data that must remap on context switches, for user page tables (memory map), and for some dynamically-allocated data areas. Kseg2 allows selective caching and mapping on a per page basis, rather than requiring an all-or-nothing approach.

The 32-bit virtual addresses generated in the registers 76 or PC 80 of the microprocessor chip and output on the bus 84 are represented in Figure 11, where it is seen that bits 0-11 are the offset used unconditionally as the low-order 12-bits of the address on bus 42 of Figure 3, while bits 12-31 are the VPN or virtual page number in which bits 29-31 select between kuseg, kseg0, kseg1 and kseg2. The process identifier PID for the currently-executing process is stored in a register also accessible by the TLB. The 64-bit TLB entries are represented in Figure 11 as well, where it is seen that the 20-bit VPN from the virtual address is compared to the 20-bit VPN field located in bits 44-63 of the 64-bit entry, while at the same time the PID is compared to bits 38-43; if a match is found in any of the sixty-four 64-bit TLB entries, the page frame number PFN at bits 12-31 of the matched entry is used as the output via busses 82 and 42 of Figure 3 (assuming other criteria are met). Other one-bit values in a TLB entry include N, D, V and G. N is the non-



cachable indicator, and if set the page is non-cachable and the processor directly accesses local memory or global memory instead of first accessing the cache 44 or 45. D is a write-protect bit, and if set means that the location is "dirty" and therefore writable, but if zero a write operation causes a trap. The V bit means valid if set, and allows the TLB entries to be cleared by merely resetting the valid bits; this V bit is used in the page-swapping arrangement of this system to indicate whether a page is in local or global memory. The G bit is to allow global accesses which ignore the PID match requirement for a valid TLB translation; in kseg2 this allows the kernel to access all mapped data without regard for PID.

The device controllers 30 cannot do DMA into local memory 16 directly, and so the global memory is used as a staging area for DMA type block transfers, typically from disk 148 or the like. The CPUs can perform operations directly at the controllers 30, to initiate or actually control operations by the controllers (i.e., programmed I/O), but the controllers 30 cannot do DMA except to global memory; the controllers 30 can become the bus (bus 28) master and through the I/O processor 26 or 27 do reads or writes directly to global memory in the memory modules 14 and 15.

Page swapping between global and local memories (and disk) is initiated either by a page fault or by an aging process. A page fault occurs when a process is executing and attempts to execute from or access a page that is in global memory or on disk; the TLB 83 will show a miss and a trap will result, so low level trap code in the kernel will show the location of the page, and a routine will be entered to initiate a page swap. If the page needed is in global memory, a series of commands are sent to the DMA controller 74 to write the least-recently-used page from local memory to global memory and to read the needed page from global to local. If the page is on disk, commands and addresses (sectors) are written to the controller 30 from the CPU to go to disk and acquire the page, then the process which made the memory reference is suspended. When the disk controller has found the data and is ready to send it, an interrupt is signalled which will be used by the memory modules (not reaching the CPUs) to allow the disk controller to begin a DMA to global memory to write the page into global memory, and when finished the CPU is interrupted to begin a block transfer under control of DMA controller 74 to swap a least used page from local to global and read the needed page to local. Then, the original process is made runnable again, state is restored, and the original memory reference will again occur, finding the needed page in local memory. The other mechanism to initiate page swapping is an aging routine by which the operating system periodically goes through the pages in local memory marking them as to whether or not each page has been used recently, and those that have not are subject to be pushed out to global memory. A task switch does not itself initiate page swapping, but instead as the new task begins to produce page faults, pages will be swapped as needed, and the candidates for swapping out are those not recently used.

If a memory reference is made and a TLB miss is shown, but the page table lookup resulting from the TLB miss exception shows the page is in local memory, then a TLB entry is made to show this page to be in local memory. That is, the process takes an exception when the TLB miss occurs, goes to the page tables (in the kernel data section), finds the table entry, writes to TLB, then the process is allowed to proceed. But if the memory reference shows a TLB miss, and the page tables show the corresponding physical address is in global memory (over 8M physical address), the TLB entry is made for this page, and when the process resumes it will find the page entry in the TLB as before; yet another exception is taken because the valid bit will be zero, indicating the page is physically not in local memory, so this time the exception will enter a routine to swap the page from global to local and validate the TLB entry, so execution can then proceed. In the third situation, if the page tables show address for the memory reference is on disk, not in local or global memory, then the system operates as indicated above, i.e., the process is put off the run queue and put in the sleep queue, a disk request is made, and when the disk has transferred the page to global memory and signalled a command-complete interrupt, then the page is swapped from global to local, and the TLB updated, then the process can execute again.

#### Private Memory:

Although the memory modules 14 and 15 store the same data at the same locations, and all three CPUs 11, 12 and 13 have equal access to these memory modules, there is a small area of the memory assigned under software control as a private memory in each one of the memory modules. For example, as illustrated in Figure 12, an area 155 of the map of the memory module locations is designated the private memory area, and is writable only when the CPUs issue a "private memory write" command on bus 59. In an example embodiment, the private memory area 155 is a 4K page starting at the address contained in a register 156 in the bus interface 56 of each one of the CPU modules; this starting address can be changed under software control by writing to this register 156 by the CPU. The private memory area 155 is further divided between the three CPUs; only CPU-A can write to area 155a, CPU-B to area 155b, and CPU-C to

area 155c. One of the command signals in bus 57 is set by the bus interface 56 to inform the memory modules 14 and 15 that the operation is a private write, and this is set in response to the address generated by the processor 40 from a Store instruction; bits of the address (and a Write command) are detected by a decoder 157 in the bus interface (which compares bus addresses to the contents of register 156) and used to generate the "private memory write" command for bus 57. In the memory module, when a write command is detected in the registers 94, 95 and 96, and the addresses and commands are all voted good (i.e., in agreement) by the vote circuit 100, then the control circuit 100 allows the data from only one of the CPUs to pass through to the bus 101, this one being determined by two bits of the address from the CPUs. During this private write, all three CPUs present the same address on their bus 57 but different data on their bus 58 (the different data is some state unique to the CPU, for example). The memory modules vote the addresses and commands, and select data from only one CPU based upon part of the address field seen on the address bus. To allow the CPUs to vote some data, all three CPUs will do three private writes (there will be three writes on the busses 21, 22 and 23) of some state information unique to a CPU, into both memory modules 14 and 15. During each write, each CPU sends its unique data, but only one is accepted each time. So, the software sequence executed by all three CPUs is (1) Store (to location 155a), (2) Store (to location 155b), (3) Store (to location 155c). But data from only one CPU is actually written each time, and the data is not voted (because it is or could be different and could show a fault if voted). Then, the CPUs can vote the data by having all three CPUs read all three of the locations 155a, 155b and 155c, and by having software compare this data. This type of operation is used in diagnostics, for example, or in interrupts to vote the cause register data.

The private-write mechanism is used in fault detection and recovery. For example, if the CPUs detect a bus error upon making a memory read request, such as a memory module 14 or 15 returning bad status on lines 33-1 or 33-2. At this point a CPU doesn't know if the other CPUs received the same status from the memory module; the CPU could be faulty or its status detection circuit faulty, or, as indicated, the memory could be faulty. So, to isolate the fault, when the bus fault routine mentioned above is entered, all three CPUs do a private write of the status information they just received from the memory modules in the preceding read attempt. Then all three CPUs read what the others have written, and compare it with their own memory status information. If they all agree, then the memory module is voted off-line. If not, and one CPU shows bad status for a memory module but the others show good status, then that CPU is voted off-line.

#### Fault-Tolerant Power Supply:

Referring now to Figure 13, the system of the preferred embodiment may use a fault-tolerant power subsystem which provides the capability for on-line replacement of failed power supply modules, as well as on-line replacement of CPU modules, memory modules, I/O processor modules, I/O controllers and disk modules as discussed above. In the circuit of Figure 13, an a/c power line 160 is connected directly to a power distribution unit 161 that provides power line filtering, transient suppressors, and a circuit breaker to protect against short circuits. To protect against a/c power line failure, redundant battery packs 162 and 163 provide sufficient system power so that orderly system shutdown can be accomplished; for example, several minutes (e.g., four and one-half) of battery power is sufficient in an illustrative embodiment. Only one of the two battery packs 162 or 163 is required to be operative to safely shut the system down.

The power subsystem has two identical AC to DC bulk power supplies 164 and 165 which exhibit high power factor and energize a pair of 36-volt DC distribution busses 166 and 167. The system can remain operational with one of the bulk power supplies 164 or 165 operational.

Four separate power distribution busses are included in these busses 166 and 167. The bulk supply 164 drives a power bus 166-1, 167-1, while the bulk supply 165 drives power bus 166-2, 167-2. The battery pack 162 drives bus 13, 167-3, and is itself recharged from both 166-1 and 166-2. The battery pack 163 drives bus 13, 167-3 and is recharged from busses 166-1 and 167-2. The three CPUs 11, 12 and 13 are driven from different combinations of these four distribution busses.

A number of DC-to-DC converters 168 connected to these 36-v busses 166 and 167 are used to individually power the CPU modules 11, 12 and 13, the memory modules 14 and 15, the I/O processors 26 and 27, and the I/O controllers 30. The bulk power supplies 164 and 165 also power the three system fans 169, and battery chargers for the battery packs 162 and 163. By having these separate DC-to-DC converters for each system component, failure of one converter does not result in system shutdown, but instead the system will continue under one of its failure recovery modes discussed above, and the failed power supply component can be replaced while the system is operating.

The power system can be shut down by either a manual switch (with standby and off functions) or

under software control from a maintenance and diagnostic processor 170 which automatically defaults to the power-on state in the event of a maintenance and diagnostic power failure.

#### System-bus Error Evaluation:

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The sequences used by the CPUs 11, 12 and 13 to evaluate responses by the memory modules 14 and 15 to transfers via buses 21, 22 and 23 (the system-bus) will now be described. This sequence is defined by the state machine in the bus interface units 56 and in code executed by the CPUs.

In case one, of a read transfer, it is assumed that no data errors are indicated in the status bits on lines 10 33 from the primary memory. The stall begun by the memory reference is not ended until the other (non-primary) memory module responds with an ending status condition or the non-primary memory times out. The stall is terminated by asserting a Ready signal via control bus 55 and 43. If the non-primary memory asserts an acknowledge on line 112 before the time out expires, the ending status is evaluated by the state machine. In no data errors are indicated by either status field (lines 33-1 or 33-2), the memory reference is 15 terminated without any further action.

In case two, for read transfer, it is assumed that no data errors are indicated from the primary memory on lines 33-1 and that the non-primary memory acknowledges and indicates a data error in the status received on lines 33-2. In this situation, the memory reference is ended as in case one and in addition the ending status condition is latched in a register and an interrupt is posted. If either the primary memory 20 and/or the non-primary memory indicate an error on lines 33 other than a data error, then the reference is terminated and the status is latched with an interrupt posted. Another variation of case two is that the non-primary memory fails to assert an acknowledge before the time out expires. In this case, the interrupt is posted along with an indication to software that a time out occurred during a read transfer on the non-primary memory.

In case three, for read transfer, it is assumed that a data error is indicated in status lines 33 from the 25 primary memory or that no response is received from the primary memory. The CPUs will wait for an acknowledge from the other memory, and if no data errors are found in the status bits from the other memory, circuitry of the bus interface 56 forces a change in ownership (primary memory ownership status), then a retry is instituted to see if data is correctly read from the new primary. If good status is received 30 from the new primary (no data error indication), then the stall is ended as before, and an interrupt is posted along with an ownership change indication to update the system (to note one memory bad and different memory is primary). However, if a data error or timeout results from this attempt to read from the new primary, then a bus error is indicated to the processor 40 via control bus 55 and 43.

In case four, for read transfer, if both the primary memory and the non-primary memory indicate a data 35 error in status lines 33-1 and 33-2, or if no response is received from the primary memory and the other memory responds with a status error in lines 33, the stall is ended and a bus error is indicated to the processor 40 via control bus 55 and 43.

For write transfers, with the write buffer 50 bypassed, case one is where no data errors are indicated in status lines 33-1 and 33-2 from either memory module. The stall is ended to allow execution to continue.

For write transfers, with write buffer 50 bypassed, case two is where no data errors are indicated from 40 the primary memory on lines 33-1 and that the non-primary memory acknowledges and indicates a data error in the status received on lines 33-2. In this situation, the memory reference is ended as in case one and in addition the ending status condition is latched in a register and an interrupt is posted. If either the primary memory and/or the non-primary memory indicate an error on lines 33 other than a data error, then 45 the reference is terminated and the status is latched with an interrupt posted. Another variation of case two is that the non-primary memory fails to assert an acknowledge before the time out expires. In this case, the interrupt is posted along with an indication to software that a time out occurred during a write transfer on the non-primary memory.

For write transfers, with write buffer 50 bypassed, case three is where a data error is indicated in status 50 from primary memory, or no response is received from the primary memory. The interface controller of each CPU waits for an acknowledge from the other memory module, and if no data errors are found in the status from the other memory, an ownership change is forced and an interrupt is posted. But if data errors or timeout occur for the other (new primary) memory module, then a bus error is asserted to the processor 40.

For write transfers, with write buffer 50 bypassed, case four is where both the primary memory and the 55 non-primary memory indicate a data error in status lines 33-1 and 33-2, or if no response is received from the primary memory and the other memory responds with a status error in lines 33, the stall is ended and a bus error is indicated to the processor 40 via control bus 55 and 43.

For write transfers, with write buffer 50 enabled so the processor 40 is not stalled by a write operation, case one is with no errors indicated in the status from either memory module. The transfer is ended, so another bus transfer may begin.

For write transfers, with write buffer 50 enabled, case two is where no data errors are indicated from the primary memory on lines 33-1 and that the non-primary memory acknowledges and indicates a data error in the status received on lines 33-2. In this situation, the memory reference is ended as in case one and in addition the ending status condition is latched in a register and an interrupt is posted. If either the primary memory and/or the non-primary memory indicate an error on lines 33 other than a data error, then the reference is terminated and the status is latched with an interrupt posted. Another variation of case two is that the non-primary memory fails to assert an acknowledge before the time out expires. In this case, the interrupt is posted along with an indication to software that a time out occurred during a write transfer on the non-primary memory.

For write transfers, with write buffer 50 enabled, case three is where a data error is indicated in status from primary memory, or no response is received from the primary memory. The interface controller of each CPU waits for an acknowledge from the other memory module, and if no data errors are found in the status from the other memory, an ownership change is forced and an interrupt is posted. But if data errors or timeout occur for the other (new primary) memory module, then an interrupt is asserted to the processor 40 and the transfer is ended.

For write transfers, with write buffer 50 enabled, case four is where both the primary memory and the non-primary memory indicate a data error in status in lines 33-1 and 33-2, or if no response is received from the primary memory and the other memory responds with a status error in lines 33, the transfer is ended and an interrupt is indicated to the processor 40 via control bus 55 and 43.

Once it has been determined by the mechanism just described that a memory module 14 or 15 is faulty, the fault condition is signalled to the operator, but the system can continue operating. The operator will probably wish to replace the memory board containing the faulty module, which can be done while the system is powered up and operating. The system is then able to re-integrate the new memory board without a shutdown. This mechanism also works to revive a memory module that failed to execute a write due to a soft error but then tested good so it need not be physically replaced. The task is to get the memory module back to a state where its data is identical to the other memory module. This revive mode is a two step process. First, it is assumed that the memory is uninitialized and may contain parity errors, so good data with good parity must be written into all locations, this could be all zeros at this point, but since all writes are executed on both memories the way this first step is accomplished is to read a location in the good memory module then write this data to the same location in both memory modules 14 and 15. This is done while ordinary operations are going, on interleaved with the task being performed. The CPUs treat a memory in revive state just as if it were in the online state, but writes originating from the I/O busses 24 or 25 are ignored by this revive routine in its first stage. After all locations have been thus written, the next step is the same as the first except that I/O accesses are also written; that is, I/O writes from the I/O busses 24 or 25 are executed as they occur in ordinary traffic in the executing task, interleaved with reading every location in the good memory and writing this same data to the same location in both memory modules. When the modules have been addressed from zero to maximum address in this second step, the memories are identical. During this second revive step, both CPUs and I/O processors expect the memory module being revived to perform all operations without errors. The I/O processors 26, 27 will not use data presented by the memory module being revived during data read transfers. After completing the revive process the revived memory can then be (if necessary) designated primary.

A similar revive process is provided for CPU modules. When one CPU is detected faulty (as by the memory voter 100, etc.) the other two continue to operate, and the bad CPU board can be replaced without system shutdown. When the new CPU board has run its power-on self-test routines from on-board ROM 63, it signals this to the other CPUs, and a revive routine is executed. First, the two good CPUs will copy their state to global memory, then all three CPUs will execute a "soft reset" whereby the CPUs reset and start executing from their initialization routines in ROM, so they will all come up at the exact same point in their instruction stream and will be synchronized then the saved state is copied back into all three CPUs and the task previously executing is continued.

As noted above, the vote circuit 100 in each memory module determines whether or not all three CPUs make identical memory references. If so, the memory operation is allowed to proceed to completion. If not, a CPU fault mode is entered. The CPU which transmits a different memory reference, as detected at the vote circuit 100, is identified in the status returned on bus 33-1 and or 33-2. An interrupt is posted and a software subsequently puts the faulty CPU offline. This offline status is reflected on status bus 32. The memory reference where the fault was detected is allowed to complete based upon the two-out-of-three

vote, then until the bad CPU board has been replaced the vote circuit 100 requires two identical memory requests from the two good CPUs before allowing a memory reference to proceed. The system is ordinarily configured to continue operating with one CPU off-line, but not two. However, if it were desired to operate with only one good CPU, this is an alternative available. A CPU is voted faulty by the voter circuit 100 if  
 5 different data is detected in its memory request, and also by a time-out; if two CPUs send identical memory requests, but the third does not send any signals for a preselected time-out period, that CPU is assumed to be faulty and is placed off-line as before.

The I/O arrangement of the system has a mechanism for software reintegration in the event of a failure. That is, the CPU and memory module core is hardware fault-protected as just described, but the I/O portion  
 10 of the system is software fault-protected. When one of the I/O processors 26 or 27 fails, the controllers 30 bound to that I/O processor by software as mentioned above are switched over to the other I/O processor by software; the operating system rewrites the addresses in the I/O page table to use the new addresses for the same controllers, and from then on these controllers are bound to the other one of the pair of I/O processors 26 or 27. The error or fault can be detected by a bus error terminating a bus cycle at the bus  
 15 interface 56, producing an exception dispatching into the kernel through an exception handler routine that will determine the cause of the exception, and then (by rewriting addresses in the I/O table) move all the controllers 30 from the failed I/O processor 26 or 27 to the other one.

When the bus interface 56 detects a bus error as just described, the fault must be isolated before the reintegration scheme is used. When a CPU does a write, either to one of the I/O processors 26 or 27 or to  
 20 one of the I/O controllers 30 on one of the busses 28 (e.g., to one of the control or status registers, or data registers, in one of the I/O elements), this is a bypass operation in the memory modules and both memory modules execute the operation, passing it on to the two I/O busses 24 and 25; the two I/O processors 26 and 27 both monitor the busses 24 and 25 and check parity and check the commands for proper syntax via the controllers 126. For example, if the CPUs are executing a write to a register in an I/O processor 26 or  
 25 27, if either one of the memory modules presents a valid address, valid command and valid data (as evidenced by no parity errors and proper protocol), the addressed I/O processor will write the data to the addressed location and respond to the memory module with an Acknowledge indication that the write was completed successfully. Both memory modules 14 and 15 are monitoring the responses from the I/O processor 26 or 27 (i.e., the address and data acknowledge signals of Figure 7, and associated status), and  
 30 both memory modules respond to the CPUs with operation status on lines 33-1 and 33-2. (If this had been a read, only the primary memory module would return data, but both would return status.) Now the CPUs can determine if both executed the write correctly, or only one, or none. If only one returns good status, and that was the primary, then there is no need to force an ownership change, but if the backup returned good and the primary bad, then an ownership change is forced to make the one that executed correctly now the  
 35 primary. In either case an interrupt is entered to report the fault. At this point the CPUs do not know whether it is a memory module or something downstream of the memory modules that is bad. So, a similar write is attempted to the other I/O processor, but if this succeeds it does not necessarily prove the memory module is bad because the I/O processor initially addressed could be hanging up a line on the bus 24 or 25, for example, and causing parity errors. So, the process can then selectively shut off the I/O processors and  
 40 retry the operations, to see if both memory modules can correctly execute a write to the same I/O processor. If so, the system can continue operating with the bad I/O processor off-line until replaced and reintegrated. But if the retry still gives bad status from one memory, the memory can be off-line, or further fault-isolation steps taken to make sure the fault is in the memory and not in some other element; this can include switching all the controllers 30 to one I/O processor 26 or 27 then issuing a reset command to the  
 45 off I/O processor and retry communication with the online I/O processor with both memory modules live - then if the reset I/O processor had been corrupting the bus 24 or 25 its bus drivers will have been turned off by the reset so if the retry of communication to the online I/O processor (via both busses 24 and 25) now returns good status it is known that the reset I/O processor was at fault. If both memory modules acknowledge with any type of error other than a data error, then the I/O transfer is terminated and a bus  
 50 error is indicated to the processor. A time out is handled the same way. If the primary responds with a data error and the backup has no data error, then an ownership change is attempted. In any event, for each bus error, some type of fault isolation sequence is implemented to determine which system component needs to be forced offline.

#### 55 CPU and Memory Error Recovery:

Handling of hardware faults in the CPU and memory subsystem of Figures 1-13 is an important feature. The subsystem includes the CPUs 11, 12 and 13 and the memory boards 14 and 15, along with the

system-bus, i.e., buses 21, 22 and 23. Whenever the hardware detects some extraordinary event, whether a small glitch such as a memory parity error, or a major subsystem failure (a blown power supply, for instance), the object is to identify the failed component and remove it from the system so that normal operation may quickly resume; at this point no attempt is made to diagnose or reintegrate the failed component. First the error recovery arrangement for the "core" of the system will be discussed, then the error recovery for the I/O buses and I/O controllers.

Hardware Error Exceptions: Hardware error exceptions are indicated by high priority interrupts or by bus errors. In general a high priority interrupt is generated for an error that can be handled asynchronously, i.e. sometime after the current instruction is executed. A few examples are (1) a "take ownership" operation forced by hardware-detected fault on previous primary memory board 14 or 15; (2) Non-data errors on system-bus reads; (3) system-bus reads that suffered a data error on the primary memory 14 or 15, but still could be completed by the backup memory 14 or 15. In these three examples, the kernel is notified of errors from which the hardware has already recovered. In some cases, however, the processor is stalled awaiting the finish of an operation that can never be completed, such as: (1) failed take-ownership operations; (2) system-bus reads and writes that can be completed by neither memory module; (3) data errors on system-bus writes while the write buffer 52 is enabled. Since interrupts can be masked, they can't be relied upon to break a stall; bus errors perform this function.

Even though these two types of hardware error exception are thus distinguished, nevertheless the two can be funneled into one exception handler that doesn't care which type occurred. During its pass through the bus error handler, if a bus error isn't recognized as being caused by 'nofault' or subscription services accesses or as resulting from user stack growth, it is shunted off to the hardware fault code (which happens to be the handler for high priority interrupts). The error status preserved by the system of Figures 1-8 is equally valid for either type of exception.

The first error registers to be checked are ones which are potentially asymmetric, since they report failures in processor synchronization.

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The CPU\_ERR register contains a number of specific bits assigned to indicate certain types of errors, as indicated in the following sub-paragraphs:

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CPU\_ERR: Interrupt synchronization error - Indicated by: CPU\_ERR\_IS bit. This indicates CPU divergence or the failure of a signal in a CPU's interrupt synchronization logic. If the soft synchronization test didn't reveal divergence, pursue the fault in synchronization hardware. Response:

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If the CPU's don't agree on the state of CPU\_ERR\_IS,  
take the odd CPU offline.

15

Else,  
soft-vote CPU\_SERR and act on bit settings as  
described below.

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CPU\_SERR: Interrupt pending inputs - Indicated by:  
CPU\_SERR\_CPUaHIGH, CPU\_SERR\_CPUbHIGH, CPU\_SERR\_CPUcHIGH,  
CPU\_SERR\_CPUaLOW, CPU\_SERR\_CPUbLOW, CPU\_SERR\_CPUcLOW,  
CPU\_SERR\_CPUaTIM0, CPU\_SERR\_CPUbTIM0, CPU\_SERR\_CPUcTIM0,  
CPU\_SERR\_CPUaTIM1, CPU\_SERR\_CPUbTIM1, or CPU\_SERR\_CPUcTIM1 bits.  
These bits present a snapshot of the inputs to the interrupt synchronization circuitry  
65 on each CPU at the instant the error was flagged. Response:

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If one CPU's version of these four inputs is unique,  
its synchronization hardware is broken; take it offline.

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CPU\_ERR: Processor synchronization error - Indicated by: CPU\_ERR\_PS bit. This indicates CPU divergence or the failure of a signal in a

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CPU's processor synchronization logic; the soft-sync operation didn't reveal divergence, so pursue the fault in synchronization hardware. Response:

If the CPU's don't agree on the state of CPU\_ERR\_PS,  
take the odd CPU offline.

Else,

soft-vote CPU\_SERR and act on bit settings as  
described below.

CPU\_SERR: Processors stalled - Indicated by:

CPU\_SERR\_CPUaSTALL, CPU\_SERR\_CPUbSTALL, CPU\_SERR\_CPUcSTALL  
bits. These bits present a snapshot of the input to the processor synchronization  
hardware on each CPU at the instant the error was flagged. Response:

If one CPU's version of this signal is unique,  
its synchronization hardware is broken; take it offline.

CPU\_ERR: Unassigned CPU space violation - Indicated by:

CPU\_SERR\_USV bit. An unimplemented address within CPU space was written.  
This may result from failing kernel software or from a fault in the CPU hardware's  
address decode logic. Note that this is one of the few cases where it does matter  
whether the exception is a bus error or high priority interrupt. For USV's, if the write  
buffer is enabled, a high priority interrupt is generated; else, a buss error. If the  
errant write goes into the write buffer, the USV will happen asynchronously and so  
the PC in the exception frame won't pinpoint the guilty instruction. Therefore, the  
type of exception tells whether to trust the exception PC. Response:

If all CPU's show an unassigned space error, the kernel has been  
corrupted;

read the bad address from CPU\_ERRADDR;  
write CPU\_MASK\_CUSV to clear the error;  
consult for required action.



Else, if only one CPU shows the error,  
take it offline.

5

CPU\_ERR: Write violation in local RAM - Indicated by: CPU\_ERR\_WPV bit. A write to a write-protected address was attempted. This may result from failing kernel software or from a fault in CPU or memory module write protect RAM. Just as for Unassigned Space Violations (see above), the exception type tells whether to trust the PC in the exception stack frame. Response:

15

If all CPU's show a write protect violation, the kernel has been corrupted;

read the bad address from CPU\_ERRADDR;

20

write CPU\_MASK\_CWPV to clear the error;

consult for required action.

Else, if only one CPU shows the error,

25

take it offline.

CPU\_ERR: Dual rail faults - Indicated by:  
CPU\_ERR\_CPUaDRF, CPU\_ERR\_CPUbDRF, CPU\_ERR\_CPUcDRF,  
CPU\_ERR\_IOP0DRF, CPU\_ERR\_IOP1DRF or CPU\_ERR\_MPDRF bits. The failure can be at the signal's source, on the backplane, or on an individual CPU. CPU\_ERR describes dual rail faults from all sources but the memory module 14 and 15. Since there are too many different dual rail signals coming from memory module to fit in CPU\_ERR, these fault bits are located in the system-bus status registers, CPU\_RSBA and CPU\_RSBC. Response:

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If all three CPU's concur that a particular DRF is present,

disable the source of the bad signal.

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Else,

disable the odd CPU (since the signal was driven inactive

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by the detection of the fault, it is likely that the  
signal's source will be disabled in the future, even  
though the culprit was a bad CPU).

**CPU\_ERR:** Power system state change interrupt - Indicated by:  
CPU\_ERR\_POWER bit. Response:

Read CPU\_POWER and act on bit settings as described below

**CPU\_POWER:** Bulk regulator and battery status - Indicated by:  
CPU\_POWER\_BATTaSTS1, CPU\_POWER\_BATTaSTS2,  
CPU\_POWER\_BATTcSTS1, CPU\_POWER\_BATTcSTS2,  
CPU\_POWER\_BULKaSTS1, CPU\_POWER\_BULKaSTS2,  
CPU\_POWER\_BULKcSTS1, CPU\_POWER\_BULKcSTS2,  
CPU\_POWER\_BATTaMON1, CPU\_POWER\_BATTaMON2,  
CPU\_POWER\_BATTcMON1, CPU\_POWER\_BATTcMON2,  
CPU\_POWER\_BULKaMON1, CPU\_POWER\_BULKaMON2,  
CPU\_POWER\_BULKcMON1, or CPU\_POWER\_BULKcMON2 bits. In this  
register, STS bits set to one indicate components which are physically present; the  
MON bits are writable masks which are initially set to the same state as their  
corresponding STS bits. A high priority interrupt is generated if any MON line doesn't  
match its STS line. Note that these double-line signals are not dual rail signals; any  
STS lines 1 and 2 should always match. Response:

save the current MON bits;  
read the current STS bits and write them to the MON bits  
(masking this power state change interrupt);  
compare the saved MON bits with the current STS bits;  
if either STS line for any battery or bulk regulator has changed  
call the powerfail interrupt handler.

CPU\_ERR: Core module present state change interrupt - At least one of the CPUs, memory modules, or I/O processors has been removed or replaced. By comparing the current module-present bits in CPU\_CFG to their previous state (saved by the kernel), the missing/added component can be identified. Response:

If a memory module or I/O Processor board has been removed,  
 hold in reset;  
 mark it as absent;  
 remove from /config.;

If a CPU board has been removed,  
 mark it as absent,  
 remove from /config.

The kernel saves the state of CPU\_CFG when returning from hardware exceptions. With this as a reference, configuration changes (boards failed, pulled, reinserted, batteries rejuvenated, and so forth) can be noticed by comparing the current and the saved versions of CPU\_CFG when the next hardware exception is taken.

CPU\_ERR: Both memory module primary error - Both memory modules claim to be primary. This is probably a result of a failed take-ownership operation. Upon detection of both memory module's primary, the CPU's complement the would-be system-bus ownership bits to switch back to the pre-take-ownership operation primary. Response:

Soft-reset the backup and take it offline.

CPU\_ERR: memory module primary and revive error - A memory module 14 or 15 claims to be both primary and in revive mode, probably due to a picked bit in the indicated memory module's control register; could also be a dual rail fault on memory module Primary. Response:

Perform take-ownership, soft-reset the backup, and take it  
offline.

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CPU\_ERR: TMRC timeout bits - Indicated by:

CPU\_ERR\_TMRCaTMOR, CPU\_ERR\_TMRCcTMOR,  
10 CPU\_ERR\_TMRCaTMOTOS, CPU\_ERR\_TMRCcTMOTOS,  
CPU\_ERR\_TMRCaTMOW, or CPU\_ERR\_TMRCcTMOW bits. Not to be  
confused with CPU\_RSB\_TMO, indicating one or more CPU's were timed out, these  
15 bits describe reasons the system-bus timed out one of the memory module 14 or 15.  
This may be the result of self-checking logic on the memory modules causing the  
board to halt because an internal error was detected. There is no other indicator of  
20 memory module internal errors. Response:

Soft-reset the memory module and take it offline.

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CPU\_ERR: RSB error - Indicated by: CPU\_ERR\_RSBA,  
CPU\_ERR\_RSBC bits. Response:

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For either or both CPU\_ERR\_RSBA bits set,  
read corresponding CPU\_RSBA register and act on bit  
settings as described below.

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CPU\_RSBA: Data vote error - Indicated by: CPU\_RSB\_ANY or  
CPU\_RSB\_CPUx bits. One CPU's data miscompares with the others; data could  
have been take-ownership, Module Present DRF, or system-bus parity signals.  
40 Response:

Take CPUx offline.

45

CPU\_RSBA: CPU timeout - Indicated by: CPU\_RSB\_ANY,  
CPU\_RSB\_TMO, or CPU\_RSB/CPUx bits. Indicated CPU was the only one to miss  
(or only one to initiate) an system-bus request or a take-ownership. Response:  
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Take CPUx offline.

6 CPU\_RSBx: Data error - Indicated by: CPU\_RSB\_ANY or  
CPU\_RSB\_DATA bits. This can be any of several faults: (1) Access to valid but  
absent (uninstalled) global memory; (2) Access to non-existent global memory  
10 address; (3) Write protect violation in global memory; (4) Data error (parity error in  
data from memory). Response:

Read TMRC\_ERR;  
15 if none of TMRC\_ERR\_ABSENTRAM, TMRC\_ERR\_NEXIS-  
TRAM, or TMRC\_ERR\_WPV are set, assume  
the data error,  
20 perform take-ownership if necessary, making the failed  
memory module backup;  
soft-reset the backup;  
25 take the backup offline.

TMRC\_ERR: Access to uninstalled global RAM - Indicated by:  
30 TMRC\_ERR\_NEXISTRAM bit. Response:  
Perform action analogous to that for local RAM write protect  
violations.  
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TMRC\_ERR: Access to non-existent global RAM - Indicated by:  
40 TMRC\_ERR\_ABSENTRAM bit. Response:  
Perform action analogous to that for local RAM write protect  
violations.

45 TMRC\_ERR: Write protection violation in global RAM - Indicated  
by: TMRC\_ERR\_WPV or TMRC\_ERR\_CPU bits. This error can be caused by  
CPU access or by a VME master writing into global RAM; TMRC\_ERR\_CPU tells  
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which is the culprit. The address of the attempted write is latched in TMRC\_ERR-ADDR. Response:

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If the CPU initiated the write,  
perform action analogous to that for local RAM write  
protect violations;

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else,  
treat as a master access fault.

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CPU\_RSBx: Bypass error - Indicated by: CPU\_RSB\_ANY,  
CPU\_RSB\_RIOB or CPU\_RSB\_DATA bits. The I/O processor returned bad status  
or the memory module detected a parity error on data read from the I/O processor.  
The problem could stem from the memory module or from the I/O-bus interface logic  
on the I/O processor. Another possibility is that the other I/O processor sharing the  
I/O-bus has failed in such a way that it is causing I/O-bus operations to fail.

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Response:

If both system-bus's show the RIOB/IOP bit set,  
take the I/O processor out.

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Else,

If the memory module showing these system-bus status  
bits isn't primary,

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perform take-ownership;

select the other I/O processor;

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if bypass operations succeed,

disable the I/O processor;

else,

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soft-reset the memory module and take it offline.

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CPU-RSBx: Bypass timeout - Indicated by: CPU\_RSB\_ANY, CPU\_RSB\_RIOB, CPU\_RSB\_DATA or CPU\_RSB\_TMO bits. An I/O processor  
 5 26 or 27 didn't respond to a bypass operation. As above, the problem could be caused by the memory module or by the I/O-bus interface logic on the I/O processor.  
 Response:

10 If both system-bus's show the TIMEOUT bit set,  
 take the I/O processor out.

Else,

15 if the memory module showing these system-bus status  
 bits isn't primary,

perform take-ownership;  
 20 select the other I/O processor;  
 if bypass operations succeed,  
 disable the I/O processor;

25 else,

soft-reset the memory module and take it offline.

30 CPU-RSBx: Timeout on one RIOB and one CPU - Indicated by:  
 CPU\_RSB\_ANY, CPU\_RSB\_RIOB, CPU\_RSB\_DATA, CPU\_RSB\_TMO, or  
 CPU\_RSB\_CPUx bits. There are several possibilities: (1) A bypass error (see above)  
 35 accompanied by a CPU timeout; (2) a bypass timeout (see above) with a vote fault;  
 (3) an I/O processor and CPU that timed out separately. Response:

40 Take CPUx offline and retry the operation, hoping to produce  
 one of the simpler cases.

45 CPU-RSBx: Dual rail faults - Indicated by:  
 CPU\_RSB\_PRIDRF, CPU\_RSB\_HIGHDRF, CPU\_RSB\_LOWDRF,  
 CPU\_RSB\_TIM1DRF, CPU\_RSB\_TIM0DRF, CPU\_RSB\_CPUaONLDRF,  
 50 CPU\_RSB\_CPUbONLDRF, CPU\_RSB\_CPUCONLDRF,

CPU\_RSB\_TMRCaONLDRF, CPU\_RSB\_TMRCcONLDRF,  
CPU\_RSB\_REVDRF or CPU\_RSB\_PRESDRF bits. If CPU\_RSB\_PRESDRF (the  
module-present dual rail fault) has failed, since it qualifies all the rest, no dual rail  
faults from the memory module will be asserted. Response:

If the other system-bus agrees with the dual rail faults found here,  
disable the source of the signal;  
else,  
soft-reset the memory module and take it offline.

CPU\_ERR: Hardware ownership change - Indicated by:  
CPU\_ERR\_TOS bit. A take-ownership operation was forced by hardware in  
response to an system-bus error. Should also see CPU\_ERR\_RSBA or CPU\_ERR-  
\_RSBc set. Response:

Act upon CPU\_RSB status bits for the indicated system-bus.

CPU\_ERR: No bits set. Response:  
Check for memory module errors.

TRMC\_CAUSE: Inter-TMRC communication error - Indicated by  
assigned bit. An error was detected in the communication between the primary and  
backup TMRC's. Response:

Soft-reset the backup TMRC and take it offline.

TMRC\_CAUSE: Refresh counter overflow - Indicated by assigned  
bit. Global RAM hasn't been refreshed within the timeout period implemented by  
the refresh counter.



TMRC\_CAUSE: CPU module present dual rail fault - Indicated by assigned bits (one bit per CPU). Error in module present signal from one CPU.

Response:

Take the indicated CPU offline.

TMRC\_CAUSE: RIOB timeout - Indicated by assigned bit. The I/O-bus arbiter granted the bus to an I/O processor that never acknowledged the grant.

Response:

Disable the indicated I/O processor.

Some of the bits in the foregoing subparagraphs have the following meanings:

CPU_RSB_ANY	One or more of the other seven error bits is set; aka "bit <6>".
CPU_RSB_DATA	Either invalid data was read or data couldn't be correctly written; aka "bit <6>".
CPU_RSB_RIOB	Error on IOP or in RIOB interface logic; aka "bit <4>".
CPU_RSB_TMO	One or more CPU's were timed out during RSB operation, or there was an RIOB error on a bypass operation; aka "bit <3>".
CPU_RSB_CPUa	CPU a is suspected in RSB error; aka "bit <2>".
CPU_RSB_CPUb	CPU b is suspected in RSB error; aka "bit <1>".
CPU_RSB_CPUC	CPU c is suspected in RSB error; aka "bit <0>".

#### I/O Subsystem Fault Detection, Error Recovery and Reintegration:

Each of the I/O processors 26, 27, is a self-checked, fail-fast controller, the purpose being to minimize risk to the core of the system during a hardware failure. Combined with the BIM 29, each I/O processor 26, 27 also protects the CPU and Memory Subsystem from errant VME controllers 30. Unlike CPU/memory subsystem failures, software is solely responsible for recovering from an I/O processor 26, 27 failure and providing the redundancy necessary to recover from such a fault. The recovery procedure for various known I/O processor 26, 27 and controller 30 faults will be described in the following paragraphs.

The purpose here is to describe the handling of faults within the I/O subsystem of the system of Figures 1-8. When a fault in the I/O subsystem occurs, the primary goal is to identify the failed component, i.e., an I/O processor 26, 27, or I/O controller 30, or I/O device 148 and to remove it from the system configuration so that normal operation can resume.

In the following sections, headings are formed from two components: a register name and an error condition that can be described by the register. Names for registers and their bits come from the kernel's C language header files for the CPU and I/O processor 26, 27 boards. The pertinent bits within the register are

listed under an "Indicated by:" subheading. The list of bits is normally followed by a brief explanation of the error. The section is concluded by a description of the appropriate response or procedure, whether to take immediate action or to gather more information.

I/O Processor Recovery Strategies: When an I/O processor 26, 27 fails, the kernel switches the I/O controllers 30 to the other bus 28 for the other controller 26 or 27 before resetting the failed IOP controller 26 or 27.

The process to switch a controller is as follows:

- a) Acquire the bus 28 of the good I/O processor 26 or 27.
- b) Call an identification routine of each device connected to the failed I/O processor. The identification routine should, at a minimum, probe the controller 30 to see if it responds.
- c) If the identification routine fails, Take the controller 30 off-line. It could not be switched over.
- d) After switching all the controllers 30, release the bus 28.
- e) Merge the bad I/O processor's registers with the good I/O processor's registers. All I/O processor registers are mirrored in local memory 16 so that the old values are available if the I/O processor fails.
- f) Place the bad I/O processor in reset.
- g) If the exception type was a bus error and not a high priority interrupt and the instruction that was bus errored is a write to an I/O processor register, Change the contents of the source register to reflect a possibly new value in the target I/O processor register and restart the last instruction.

I/O Controller Recovery Strategies: The architecture of the system of Figure 1 does not provide for replicated I/O controllers 30. There are features provided in the operating system, such as disk mirroring, that allow the system to continue when an I/O controller 30 fails. The kernel also provides services to device drivers to detect and handle hardware faults (bus errors, parity errors, and access errors, for example). In addition, the device drivers are responsible for detecting software or firmware errors associated with their I/O controller 30. Some of the services provided are:

- iobuscopyin and iobuscopyout protect the device driver from bus errors, parity errors, and time outs (otherwise, the device driver must detect these events). They also simplify the driver's interface to the I/O processor's hardware.
- Subscription services for errors asynchronous to the CPU and for bus errors, parity errors, and time outs when the device driver chooses to bypass the iobuscopyin and iobuscopyout functions.
- Recovery techniques to back out of an instruction stream when a controller 30 fails.

When an I/O controller 30 fails, the operating system loses the resources that the controller provided. Any system calls using those resources fail unless the resource is replicated in software. In one embodiment, disk drives 148 are the only replicated peripheral devices in the system. Other embodiments may have replicated ethernet or other communications devices such that a single failed I/O controller 30 will not impact system availability on a network.

I/O processor Hardware Error Exceptions - Indicated by: I/O processor High Priority Interrupts, or CPU Bus Errors. In general, a high-priority interrupt is generated whenever the I/O processor determines that an error occurs asynchronous to current CPU activity. Some examples of these kinds of errors are: (1) Invalid access to the memory board 14 or 15 from a controller 30; (2) Invalid parity on the bus 28; (3) Invalid request from a controller 30. In each of these examples, a minimum amount of recovery has been performed by the I/O processor hardware. It is up to the kernel to kick-off the services to recover from the fault or to designate a component as failed.

When the CPU is accessing the I/O processor 26 or 27 or accessing an I/O controller 30, an I/O processor or controller failure may result in bad status being returned to the CPU board. When the CPU 11, 12 and 13 receives bad status, a bus error trap is generated by the processor. Some examples of these kinds of errors are:

- (1) Invalid parity on the bus 28; (2) controller 30 not present or failed; (3) I/O processor 26 or 27 not present or failed.

The manner in which the kernel detects an I/O processor or controller 30 failure determines the algorithm to recover. When a high-priority interrupt is captured, the kernel must determine the type of fault (I/O processor or controller), and take failed components off-line. Any recovery beyond this action is fault specific. When a bus error occurs, the kernel must always inspect the target address for a store instruction

to an I/O processor register. The target address is the address on the bus when the bus error exception occurred. It is acquired by disassembling the instruction that was executing when the bus error occurred. The I/O processor register may have been modified by the recovery process and if the write were to complete without change, it could incorrectly destroy some important bits.

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High Priority Interrupts - Indicated by: TMRC\_CAUSE\_IOP0HIGH  
or TMRC\_CAUSE\_IOP1HIGH bits. A high-priority interrupt is generated whenever  
the I/O processor detects an error within its own logic or an error in the path to or  
from a controller 30. Response:

Select the interrupting I/O processor on the memory module and call  
the I/O processor's handler.

Read the I/O processor's interrupt cause register.

If the memory module times out the read,

Move all the controllers on the I/O processor to the other,  
functioning I/O processor.

Place the I/O processor in reset.

Exit the interrupt handler.

Check each bit in the interrupt cause register, and if  
active, call the appropriate fault handler.

Exit the interrupt handler.

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IOP\_IICAUSE: Controller Bus Hog Time-out - Indicated by:  
IOP\_IICAUSE\_BUSHOG bit. A controller 30 has held the bus 28 for a very long  
time and the timer maintained by the I/O processor 26 or 27 has expired. Response:

Notify any subscribers of the bus hog error for the indicated  
slot.

If there is no subscriber or the subscriber returns 0,  
take the controller 30 off-line.

If the subscriber returns 1,  
just clear the interrupt.

IOP\_IICAUSE: Level 2 fault - Unsupported Request - Indicated by:  
IOP\_IICAUSE\_LEVEL2 bit. The controller 30 has presented the I/O processor with  
a request that is not supported. It could be an invalid address modifier, an A16  
master access, or an unsupported A32 address. Response:

Notify any subscribers of the level 2 fault for the indicated  
slot.

If there is no subscriber or the subscriber returns, 0,  
take the controller 30 off-line.

If the subscriber returns 1,  
just clear the interrupt.

IOP\_IICAUSE: Access Validation Fault - Indicated by: IOP\_IICAUSE\_AV bit. A controller 30 has attempted to access a physical address that has not  
been prepared for it by the CPU (the controller does not have the proper read/write  
permissions or slot number set up in the access validation RAM on the I/O processor).  
Response:

Notify any subscribers of the access validation fault.

If there is no subscriber or the subscriber returns, 0,  
take the controller 30 off-line.

If the subscriber returns 1,  
clear the interrupt.

5

IOP\_IICAUSE: Protocol Violation - Indicated by: IOP\_IICAUSE\_PROTO bit. The controller 30 presented the I/O processor with an invalid set of bus signals. The controller 30 may have failed. Response:

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Notify any subscribers of the protocol fault for the indicated slot.

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If there is no subscriber or the subscriber returns 0,  
take the controller 30 off-line.

If the subscriber returns 1,  
just clear the interrupt.

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IOP\_IICAUSE: parity error - Slave state machine - Indicated by: IOP\_IICAUSE\_VME\_S\_PAR bit. The I/O processor detected bad parity from the controller 30. In this case, the controller was performing an operation and the data, address, or control parity was not correct. Response:

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Notify any subscribers of the parity error for the indicated slot.

If there is no subscriber or the subscriber returns 0,  
take the controller 30 off-line.

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If the subscriber returns 1,  
just clear the interrupt.

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IOP\_IICAUSE: Bad Parity on the I/O-bus - Indicated by: IOP\_IICAUSE\_RIOB0PAR or IOP\_IICAUSE\_RIOB1PAR bits. A parity error was detected by the I/O processor 26 or 27 when accessing global memory 14 or 15. If both I/O-buses 24 and 25 present the error, then the I/O processor is at fault. If only one I/O-bus presents the error, then the memory module 14 or 15, the I/O-bus, or the I/O processor may be at fault. The memory module will be taken off-line as it may have

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stale data. Time to further isolate this fault should be scheduled at a later time.

Response:

5                   If both I/O-buses present the parity error,  
                     Switch all controllers to the other I/O processor.  
                     Take the indicated I/O processor off-line.  
 10                  If only one I/O-bus presents the parity error,  
                     Take the indicated memory module off-line.  
                     Notify any subscribers of the I/O-bus parity error.

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IOP\_IICAUSE: The I/O-bus timed out an I/O processor request -  
 Indicated by: IOP\_IICAUSE\_RIOB0TIME or IOP\_IICAUSE\_RIOB1TIME bits. A  
 20                  memory module did not respond to an I/O processor request. If both I/O-buses timed  
                     out, the I/O processor probably failed. If only one I/O-bus timed out, then the  
                     memory module, the I/O-bus, or the I/O processor may be at fault. The memory  
 25                  module will be taken off-line as it may have stale data. Time to further isolate this  
                     fault should be scheduled at a later time. Response:

30                   If both I/O-buses timed out,  
                     Switch all controllers to the other I/O processor.  
                     Take the indicated I/O processor off-line.  
                     If only one I/O-bus timed out,  
 35                   Take the indicated memory module off-line.  
                     Notify any subscribers of the I/O-bus time out.

40

IOP\_IICAUSE: Bad Status from the memory module returned to the  
 I/O processor - Indicated by: IOP\_IICAUSE\_MEM0 or IOP\_IICAUSE\_MEM1  
 45                  bits. An access to non-existent global memory, a write to protected global memory,  
                     or bad parity on an operation to global memory can cause the memory module to  
                     generate bad status to the I/O processor. If both memory modules returned bad  
 50                  status, the source of the request, a controller 30, may have failed. If only one memory

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module returned bad status, then the memory module, the I/O-bus, or the I/O processor may be at fault. The memory module will be taken off-line as it may have stale data. Time to further isolate this fault should be scheduled at a later time.

Response:

If both memory modules return bad status,

Determine the faulty controller 30 access from the I/O processor's error registers and the access validation.

Notify any subscribers of the bad status.

If there is no subscriber or the subscriber returns 0, take the indicated controller 30 off-line.

If the subscriber returns 1, just clear the interrupt.

If only one memory module returned bad status,

Take the indicated memory module off-line.

Notify any subscribers of the bad status.

**IOP\_IICAUSE:** A I/O-bus grant timed out - Indicated by: IOP\_IICAUSE\_RIOBGTIME bit. A I/O-bus grant was not received before the time out interval. When the I/O processor requested the I/O-bus, the primary memory module did not respond with the grant signal. The primary memory module or the I/O-bus may be at fault. Response:

Notify any subscribers of the timed out I/O-bus.

Make the backup memory module primary.

**CPU Bus Errors** - When the CPU is accessing registers on the I/O processor 26 or 27 or controllers 30 on the bus 28, the kernel must be prepared to receive a bus error. If the I/O processor times out an access to a controller 30 or detects some kind of error, it will generate bad status back to the memory module 14

or 15. Bits in the I/O processor's cause register can be used to isolate the error. The memory module can also time out the I/O processor, resulting in a bad status being returned to the CPU. To recover from a bus error, the kernel, after changing the configuration, must re-run the last instruction, or return execution to some known point in the previously executed instruction stream. The "known point" must be in the same thread as the error condition so that stack and user pages are properly mapped when restarted.

CPU\_RSBx: Parity error on the I/O-bus - Indicated by: CPU\_RSBx\_ANY, CPU\_RSB\_RIOB or CPU\_RSB\_DATA bits. The memory module detected a parity error on a data read from the I/O processor. If the error happened on both I/O-bus interfaces, the I/O processor has a failure. If the parity error is reported on only one I/O-bus interface, either a memory module, the I/O-bus, or one of the I/O processors failed. At least one memory module was able to get good status so a bus error is not generated. Instead, this error is reported via an interrupt. Response:

If the parity error is reported by both I/O-bus interfaces,  
 Notify any subscribers of the failed IOP.  
 Take the indicated IOP off-line.

If the parity error is reported on one I/O-bus interfaces,  
 Probe the other I/O processor.  
 If the probe fails,

Take the indicated memory module off-line.

If the probe succeeds,  
 Notify any subscribers of the failed IOP.  
 Take the indicated I/O processor off-line.

CPU\_RSBx, IOP\_IICAUSE, IOP\_STS: The BIM detected a parity error  
 - Indicated by: CPU\_RSBx\_ANY, CPU\_RSB\_RIOB,



CPU\_RSB\_DATA, IOP\_IICAUSE\_XFER and IOP\_STS\_SYSFAIL bits. The BIM  
 29 detected bad parity from the I/O processor 26 or 27 and isolated the controller 30  
 5 from the bus 28. The actual error is similar to a bus timeout except that an additional  
 error indication is asserted by the BIM. The controller must be switched to the other  
 I/O processor to recover the controller. Response:

10 Notify any subscribers of the parity error for the indicated slot.

If there is no subscriber or the subscriber returns 0,  
 take the controller 30 off-line.

15 If the subscriber returns 1,  
 exit the bus error exception.

20 CPU\_RSBx, IOP\_IICAUSE: Bus parity error - Master state machine  
 - Indicated by: CPU\_RSBx\_ANY, CPU\_RSB\_RIOB,  
 CPU\_RSB\_DATA and IOP\_IICAUSE\_M\_PAR bits. The I/O processor detected  
 25 bad bus parity from the controller 30. In this case, the CPU was performing a "read"  
 when a parity error was detected on the data lines from the controller 30. Response:

30 Notify any subscribers of the parity error for the indicated  
 slot.

If there is no subscriber or the subscriber returns 0,  
 take the indicated controller 30 off-line.

35 If the subscriber returns 1,  
 exit the bus error exception.

40 CPU\_RSBx, IOP\_IICAUSE: VMEbus time out - Controller access time  
 out - Indicated by: CPU\_RSBX\_ANY, CPU\_RSB\_RIOB,  
 CPU\_RSB\_DATA and IOP\_IICAUSE\_XFER bits. The I/O processor timed out  
 45 a request to a controller 30 or the controller responded with a bus error. Response:

50 Notify any subscribers of the bus error for the indicated  
 slot.

If there is no subscriber or the subscriber returns, 0,  
take the controller off-line.

If the subscriber returns 1,  
exit the bus error exception.

#### CPU\_RSBx IOP\_IICAUSE: I/O-bus I/O processor Select Parity Error

- Indicated by: CPU\_RSBx\_ANY, CPU\_RSB\_RIOB, CPU\_RSB\_DATA,  
CPU\_RSB\_TMO and IOP\_IICAUSE\_RIOBIOSEL bits. The I/O processor detected  
bad parity on the I/O processor select bits from the memory module when the CPU  
is attempting a transparent bypass operation to a VME controller 30. Response:

Read the I/O processor cause register on the other I/O processor.

If the other I/O processor saw the parity error on the select bits,

Switch the primary memory module to backup.

Exit the Bus Error Exception and retry the last instruction.

If the other I/O processor did not see the parity error on the select bits,  
switch the controllers to the other I/O processor.

Take the I/O processor off-line.

#### Reintegration of Memory and CPU

The fault tolerant computer system of Figures 1-13 is able to detect and isolate component failures without a total loss of the services of the system. Reintegration, the process of adding a new or failed component (board) to the system while the system is running, is fundamental to operation as a fault tolerant system. The reintegration into the system of CPU boards 11, 12 and 13, and memory boards 14 and 15 will now be discussed, beginning at the time immediately after a fault has been isolated through the time a component is brought back online.

When a faulty component is detected the component is reset and taken offline. To bring the component back online a reintegration of that component is required. The reintegration can be automatic, in which case the operating system attempts to reintegrate the failed component without intervention by the user, or it can be manual, at the request of a user-level program.

The reintegration process is a sequence of steps that are taken after the decision to reintegrate a component has been made. The code executed to implement the reintegration process performs the role of restoring system state after one of the following is diagnosed: (1) a bad CPU 11, 12 or 13; (2) a bad memory board 14 or 15; or (3) a bad memory page. The diagnosis is performed by an error interrupt subsystem based upon status information reported by the individual components, as discussed above. The error interrupt subsystem takes whatever action is necessary to put the system in a safe state - this usually means putting a failed component offline and in reset or powered off.

The reintegration process, in summary, is a sequence of events occurring when a component fails, generally as follows:

Interrupt occurs indicating a component failure:

Bad CPU 11, 12 or 13

5

Bad memory 14 or 15 (or bad memory page)

If bad CPU board 11, 12 or 13:

10

put bad CPU offline and reset

continue normal operation

when offline CPU indicates successful completion of power-on

self-test:

15

allocate page in global memory for LMR (local memory  
reintegration) routine and valid-page-bitmap

20

allocate page in global memory for LMR copy procedure

25

30

35

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```

    build bitmap of valid pages
    save state
    build data structure shared with PROM
5   reset all CPUs 11, 12 and 13
    (PROM code brings control back to here after reset)
10  restore state

    LMR:
15      for each page in local memory 16
          if valid bit set in valid-page-bitmap
              DMA copy page to reserved page
              in global memory
20          verify anticipated vote error
              DMA copy page back to local
              memory
25          verify no error

30      clean up (free LMR routine and its global page)
      done, continue with normal operation

35  If bad memory:
      if just a bad page, remap it
      else, put memory offline and in revive state
40      copy all memory pages to themselves
      if no errors, bring back online

```

45 Figure 14 shows the process of monitoring all modules for faults and placing a faulty module offline and Figure 15 shows the reintegration process. In Figure 14, the interrupt handler routines, indicated by block 171, evaluate an interrupt to see if it is produced by a hardware fault; if not, the ordinary interrupt processing sequences are entered as indicated by block 172, but, if so, then fault isolation code is entered as indicated by block 173. The fault isolation code can also be entered if a bus error is detected. The fault  
50 isolation code determines which component is down, as indicated by the blocks 174. As indicated in Figure 15, when a new component (such as a memory module 14 or 15, for example) is inserted, as indicated by the block 175, the component undergoes its power-on self-test procedure; if it fails, the component-down state is entered again as indicated by block 176, but if it passes the reintegration state is entered as indicated by the block 177. If reintegration fails then the component-down state is entered, or if it succeeds the  
55 component-online state 178 is entered.

A CPU is normally in the CPU Normal state, where the CPU is online and processing the same instruction stream as the other CPUs. When a CPU Board-Failed Status message arrives the kernel resets the failed CPU, forcing it into the CPU Dead state; a CPU comes out of reset in the CPU Dead state - the

reset is either the result of a soft reset voted by the two remaining CPUs or a hard reset if the board is just plugged in. The voters 100 on the memory board 14 or 15 ignore CPUs 11, 12 or 13 that are not online. The remaining CPUs continue with normal operation while the dead CPU attempts to execute its power-on self-test. The other state shown is the CPU Reintable state, which the previously reset CPU automatically enters if it passes the power-on self-test; this CPU remains in this state until a user request is made to reintegrate it.

There are two major steps to the CPU reintegration procedure. The first is to resynch all the CPUs 11, 12 and 13, so the offline CPU is brought back online with all three executing the same code. The second major step is to restore local memory 16, i.e., ensure that the contents of the local memory 16 on the offline CPU is identical to that of the local memory 16 on the other CPUs.

The sequence used to resynch the CPUs is:

1. Kernel raises interrupt priority.
2. Kernel saves complete processor state in preparation for reset.
3. Kernel builds data structure to tell PROMs the desired return PC value.
4. Kernel resets all CPUs.
5. PROMs put CPU and coprocessor registers in a known state.
6. PROMs verify the return PC value and jump to it.
7. Kernel restores complete CPU board state.

When a CPU fails, it is reset by the interrupt subsystem. If the failed CPU passes its power-on self-test it is eligible to be reintegrated by the remaining CPUs. Before the failed CPU can be brought back online it must be exactly in sync with the other CPUs, executing the exact same CPU cycles. The technique to accomplish this is to soft reset all CPUs. This returns all CPUs to the reset vector and allows the code in the PROMs 63 to resynch the CPUs, similar to a power-on reset.

The resynch operation occurs while the system is active, and so is fairly delicate. The code executed from the PROMs 63 for this purpose must distinguish between a power-on reset and a resynch, since a power-on reset resets all peripherals and runs memory tests which would destroy the current state of the kernel.

The reintegration code executed from the PROMs 63 keeps all the operating system dependencies in the kernel. Communication with the PROMs is through a data block, at a fixed physical memory address:

30

```

struct kernel_restart {
    ulong kr_magic;          /* magic number */
    ulong kr_pc;             /* program counter to restart */
    ulong kr_sp;             /* stack pointer */
    ulong kr_checksum;       /* checksum of above */
};

```

The magic number and checksum are used by the PROM code to verify that the return PC is valid. The magic number will only be set during a reintegration attempt. Before jumping to the return PC the code executed from the PROMs 63 puts all CPUs 11, 12 and 13 in identical states, including zeroing all CPU and coprocessor 46 registers (otherwise a random value could cause all three CPUs to disagree during a vote).

Local memory 16 is restored by using the DMA engine 74 to copy each block of local memory 16 out to global memory 14, 15, and back again; this copy-back has the effect of copying good memory to the bad. This technique relies upon two features of the system construction; first, the contents of local memory 16 are preserved across a soft reset of the CPU, and, second, the DMA engine 74 always runs to completion - in the case of a vote error, the consensus of the data will be used, and at the end of the transfer status will indicate which CPU failed the vote.

Before executing the CPU resynch step the routine which performs the DMA page copy operations is itself copied to global memory, so when the CPUs 11, 12 and 13 come out of the resynch step they will be executing this copy routine in global memory 14, 15. The two good CPUs will have the kernel and data structures 143, 144 still intact. The bad CPU will have random bad data (some test pattern) in its local memory 16. After a DMA page copy to global memory an error in voter 100 indicating a vote fault by the bad CPU is anticipated on status lines 33 and does not mean the CPU being resynched should be put offline again. On the copy from global memory back to local memory 16, however, errors indicate a problem.

In embodiments where the amount of local memory 16 is large, the time required to copy every page

may become unacceptably high. To reduce the copy time, the number of valid pages can be reduced by swapping processes out (either to disk or global memory). This reduces the number of pages that must be copied, at the expense of system response time before and after the reintegration.

If errors occur during the CPU resynch operation, all interrupts are masked by the PROM code before execution returns to the kernel. Once complete kernel state is restored the interrupt priority is lowered, and any pending error interrupts will be serviced in the usual manner. During restore of local memory 16, since the local memory is still intact on a majority of the CPUs it is possible to field non-maskable interrupts; this implies aborting the reintegration and putting the bad CPU back offline.

If local memory errors occur, differences in the contents of local memory are detected at voter 100 as vote faults during writes to global memory 14, 15. If the vote fault occurs while the write buffers 52 are enabled there is no reliable way to determine the faulty address so the error is considered fatal and the CPU board is reset. If the faulty address is known, an attempt to restore only that cell is made; if the restore is successful the board is not reset.

A parity-scrubber task is used to force vote-faults. The parity-scrubber runs in a very low-priority fashion, writing all pages from local memory 16 to a dummy page in global memory 14, 15. If any one of the three local memories 16 contains divergent data, a vote fault is detected. The parity scrubber runs with a frequency sufficient to drive toward zero the probability that all three CPUs will ever contain different data. A similar parity scrubber task runs in background at low priority to detect divergent data in global memory.

The process of detecting, isolating and placing a memory module offline is shown in Figure 15. There are two broad types of memory board failures; page specific errors (e.g., parity) that indicate only a certain page in memory has failed, and general faults that indicate the entire board has failed. General failures will reset the memory board, requiring full reintegration before the board can be brought back online. Page specific errors are handled without taking the board offline.

It is desired to make the memory boards 14, 15, "fail fast". By this is meant that when an error is present in data stored in the global memory, it will be detected in a short time, even though the data may not be accessed for a long period - that is, latent faults are intentionally sought. Two kernel-level tasks are used to make the memories fail-fast. A primary/backup swap task periodically swaps the roles of primary and backup memories 14 and 15 to ensure that errors specific to one of these modes will be detected. A parity scrubber task, as before, ensures that all pages in global memory are read by the CPUs to force latent parity errors.

The memory-normal state means the memory board 14 or 15 is online, able to function as either primary or backup. The contents of the RAM 104 is identical to that of the other memory board. The primary-backup and parity-scrubber tasks are active (at low priority). The memory-offline state is the condition in which a memory board comes out of reset; this reset is either the result of a soft reset if the board has been operating or a hard reset if the board has just been plugged in. The primary-backup and parity-scrubber tasks are turned off, since they have succeeded in crashing one memory and it is necessary that they be prevented from crashing the other. A memory board is put in the revive state by a user request to start reintegration. This revive state is a special write-only limbo state in which the memory is being prepared for reintegration. The memory board in the revive state participates in all write operations and performs write error checking as though it were online, but it does not participate in or perform error checking during reads.

At the time a memory board 14 or 15 is put in the revive state its RAM 104 is completely uninitialized. Before it can be brought back online the revive memory must contain exactly the same data as the good memory board. The reintegration process takes two passes, with each of these passes involving copying every page of memory to itself, which has the effect of reading from the good memory and writing back to both, thus copying all of the memory from the good board 14 or 15 to the revive board. The sole purpose of the first pass is to put valid parity in every location in memory so that the second pass can proceed reliably. The memory board is invisible to the I/O buses 24 and 25 during this step. The memory board 14 or 15 which is being reintegrated always returns good status to the CPUs via lines 33 during this first step. The second pass is the reintegration step, during which CPUs and I/O buses 24 and 25 write to both memory boards 14 and 15; any parity errors indicate true errors.

Depending upon the size of the global memories 14 and 15, the amount of time required to run the two reintegration passes can be significant. The user can specify how much of the total CPU resources are dedicated to the reintegration passes over a given period of time. The actual page copy is done by the kernel with priority set high and with exclusive ownership of the I/O buses 24 and 25; the priority is raised to prevent an interrupt routine from changing the data before it can be written back, and the access from the I/O buses 24 and 25 is locked out to prevent an I/O processor 26, 27 from changing data before it can be written back. The write-protect bit for a given page must be disabled while that page is being copied. The

page copy will run whenever the system is idle and at intervals specified by the user in selecting the memory reintegration policy; the block size can be selected, e.g., 128, 1024 or 4096 bytes transferred before the CPU is relinquished for other tasks, and the gap between blocks selected so the ratio of reintegration task to other tasks is defined.

- 5 If a page-specific error occurs, a set number of attempts are made to restore the page by rewriting it from the other memory (just as in full memory revive). For soft errors this corrects the problem. The memory is made primary and the page is tested before a try is considered a success. If a retry fails the memory board is reset and must be reintegrated.

#### 10 Powerfail/Autorestart:

According to another feature of this invention, the system described above is provided with a powerfail and autorestart procedure, to shut down the system in an orderly fashion upon power failure and automatically restart it when power is restored. The powerfail/autorestart procedure provides a level of  
15 transparency, in regard to the loss of AC power, to the system of Figure 1. This transparency is provided to the file system, application processes, and hardware devices. The intent is that the system will resume operation following the power failure, as if the power failure had not occurred. The powerfail/autorestart procedure provides a mechanism whereby the system may be gracefully quiesced and restarted.

The powerfail/autorestart procedure allows all applications to save state that may be resumed when  
20 power is restored. As noted above, the procedure requires the battery back-up 162, 163 to provide system power for a length of time needed to execute an orderly shutdown with the saving of state. By default, applications are not cognizant of the loss of power to the system. In order to allow for the saving of essential state, and later resumption on power restoration, the application must be configured to receive notification from the powerfail/autorestart procedure. Applications so configured may enhance the level of  
25 transparency to power loss, and recover from the time-latency intransparency already discussed.

Referring to Figure 16, a time line of a shutdown and restart procedure is illustrated. The CPUs 11, 12 and 13 are executing an instruction stream in normal operation during a time 171, and an AC power failure occurs at time 172. This power failure is signalled by the maintenance processor 170 to the CPUs 11, 12 and 13 as an interrupt, but shutdown is not immediately initiated; instead, to filter out transients, a time  
30 delay is introduced for an interval 173, after which a powerfail signal is generated by the CPUs at time 174. The shutdown process continues during a time period 175 to completion at a time 176, and if during this time the AC power has been restored the restart procedure will begin immediately at time 176. The restart procedure continues during a time period 177 to completion at time 178, as will be described. Normal operation continues during time period 179, executing the instruction stream as before shutdown during  
35 time period 171.

When the maintenance processor 170 of the power supply circuitry of Figure 8 senses a power failure, an interrupt is received by the CPUs 11, 12 and 13 that is handled by the operating system. This occurs at the time 172 of the "powerfail indication", and the shutdown procedure will not be initiated until the  
40 "powerfail confirmation" time 174. To rule out transient power failures, the CPU will wait a specified period of time 173 before proceeding with the shutdown. During this waiting period 173, the system will continue to function normally, executing the instruction stream as in the period 171. If the power failure persists, the operating system will confirm the power failure and proceed with the shutdown procedure.

The shutdown procedure is bounded in time between the powerfail confirmation 174 and the time that the batteries 162 and 163 can no longer reliably operate, which may be 4-1/2 minutes in the example given  
45 above; i.e., the shutdown time cannot be longer than 4-1/2 minutes and should be much shorter - the length will depend upon the amount of volatile memory to be copied to nonvolatile memory and the number of processes running at the time that must have state saved. During this shutdown time period 175 the active processes and device drivers will be given a warning of the impending shutdown so that they can perform any preparations necessary. Then process execution will be suspended and the state of device controllers  
50 saved. Devices not involved in the saving of system state (e.g., displays, etc.) will be powered down as soon as possible after the time 174 to minimize the power drain on the battery supplies 162 and 163. The volatile state of the kernel, processes, and device drivers will be saved to nonvolatile storage, e.g., disk 148. Finally, the battery supplies 162 and 163 will be sent a message to turn off.

When power is restored, e.g., at time 176, the system will initiate a boot sequence that differs from the  
55 norm. The normal boot procedure is automatically initiated and followed until some later stage of the bootloader checks the powerfail information in nonvolatile storage to determine if this is a normal boot or a power failure restart. In the case of a power failure restart, the essential system state is restored from nonvolatile storage rather than reloading a fresh copy of the operating system. Processes and device

drivers are allowed the opportunity to perform any procedures necessary to restart their particular application or operation.

The "essential system state", or "essential system image" (the terms are used interchangeably), consists of the volatile state of the kernel, user processes, and hardware devices. The essential system state is written to disk 148 during the powerfail shutdown. More accurately, a portion of the essential system state is written to disk. The remainder of the essential system state is already on the disk, and, as such, does not need to be written out. For example, the swap file contains portions of the executable images of processes that have been paged out; and, some file buffers for open files have been already flushed to disk.

The occurrence of a shutdown/restart cycle is transparent to many applications, but not to others. For example, if data communications sessions are established at the time of the shutdown, it is highly unlikely that the sessions will survive the shutdown/restart cycle; sessions will likely timeout and need to be reestablished. The communications controller may need to rely on some higher layer software to reestablish the communications sessions. The powerfail/autorestart procedure allows the higher layers of the software the opportunity to perform this level of recovery. A certain amount of robustness is inherent in communications protocols to handle loss of routers, packets, etc. The application may need to enhance this robustness if the shutdown/restart cycle must be transparent to its client. Any applications that are distributed in some manner across multiple processors must take advantage of the powerfail/autorestart procedure in order to supply such transparency to its users.

The occurrence of a shutdown/restart cycle may not be transparent even to a device directly attached to the local machine. For example, tape units that are rewinding may have the operation aborted. The process that requested this operation would then receive an operation failed error. In general, the shutdown/restart cycle is not transparent to any device (or process using that device) that does not stay powered up and available during the shutdown procedure time interval 175.

#### 25 File System State:

The heavily cached copy-back file system incorporated in Unix would ordinarily be expected to exhibit a lack of data integrity in the presence of system shutdown, through power failure or otherwise. A feature of the powerfail/autorestart procedure is to minimize this characteristic weakness by synchronizing the in-memory data (in local memory 16 and global memory 14, 15) with the corresponding image on disk 148.

The powerfail/autorestart procedure accomplishes this task in two ways. When the power failure is confirmed at time 174, no further delayed writes are allowed during the time 175 of the powerfail shutdown procedure, and of course all then-pending delayed writes from normal operation period 171 are executed. A "delayed" write is a disk write operation issued by an application that is held in memory for an undetermined period of time, to provide the appearance of a higher performance file system than actually exists. Since all application writes are forced to disk, the file system is kept in a synchronized state.

Also, at the time 174 of powerfail confirmation, the file system is synchronized to disk by immediately issuing all pending delayed write operations. Thus, the file system will remain synchronized as the system is gracefully quiesced and devices and processes are notified during the period 175.

Interaction between the file system and the powerfail/autorestart procedure involves the dirty file system buffers. The powerfail/autorestart procedure insures the integrity of the file system regardless of the settings of the kernel parameters chosen by the system administrator.

During the shutdown procedure, the file system dirty buffers are saved into the file system. Actually, at the time of the powerfail confirmation 174, a call is made to a routine to commence the file system synchronization. After that call, all delayed writes are forced into asynchronous writes. Later, the shutdown procedure will delay to insure that all dirty blocks have been flushed prior to the writing of the essential system image. A "delayed write" is one in which the block is not written to disk until the file system has need of any empty block and chooses this dirty block. Also, periodic file system "syncs" are done by the operating system to flush all dirty blocks. An "asynchronous write" is one in which the write is issued immediately to the disk driver. The reason for the term "asynchronous" is that the operating system will issue the request, but will not wait for its completion.

The time taken to perform this "synch" could be longer than the batteries 162 or 163 will support, a situation to be avoided. To this end, the disk device driver uses a head scheduling algorithm to insure that seek time between buffers on a given disk does not approach the average seek time for that disk. This can be accomplished by ordering the buffer writes in sequence by position on the disk.

#### Process State:



The powerfail/autorestart procedure notifies processes regarding the presence and the progress of the powerfail shutdown via UNIX® signals. In particular, the SIGPWR signal is utilized for this purpose. The powerfail/autorestart procedure has expanded the signal concept to include a "code" that is delivered to the process. Normally, Unix processes receive a signal number only, denoting the particular signal being delivered.

Referring to Figure 16, the Unix processes executing during the time 171 may be configured in one of two manners, i.e., either "kill on powerfail" or not. Each process has a "kill on powerfail" attribute that, when set, modifies the signals that are sent during the powerfail shutdown process period 175. A process marked as "kill on powerfail" is not intended to service the shutdown, although such a process may perform cleanup operations before its termination.

Additionally, processes are configured by default to "ignore" the SIGPWR signal. Such processes will not be aware that a power failure has occurred, unless the "kill on powerfail" attribute is set.

After the power failure has been confirmed at time 174, all processes are sent a signal at time 181. Processes marked as "kill on powerfail" receive the SIGTERM signal with a code of PFQUIESCE. Other processes are sent a SIGPWR signal with a code of PFQUIESCE. Some processes may ignore these signals. Note that processes which do not ignore these signals may perform some cleanup activity as required for the particular application at hand.

After an administrator-configurable interval, processes marked for "kill on powerfail" are sent the SIGKILL signal at time 182, which cannot be ignored. All other processes are suspended from execution.

The memory image of all processes is now saved in nonvolatile storage during a time 183. In certain implementations of the powerfail/autorestart procedure, this nonvolatile storage is the disk 148. Thus, the memory image in local or global memory is written to the disk 148. In other implementations, the memory boards 14 and 15 or auxiliary memory boards not shown may be battery backed up, and thus constitute nonvolatile storage.

Upon power restoration, after time 176 in the restart process, the memory image of the processes is restored during the period 177. Processes receive a SIGPWR signal with a code of PFRESTART indicating that the powerfail recovery is complete. If the process needs to restart or restore information that was archived during the shutdown procedure, it may do so now.

Thus, a process may selectively interact with the powerfail/autorestart procedure. By default, processes are not aware that a shutdown/restart cycle occurred; however, a process may make itself aware of the occurrence of either the shutdown and/or the restart. References to processes herein generally are to user processes, and not system processes. System processes do not receive any special powerfail/autorestart handling, with the exception of Init which will execute the /etc/pfshutdown or /etc/pfrestart shell script during shutdown or restart, respectively, upon receipt of the SIGPWR signal. No other system processes receive signals.

The system administrator may select certain processes to be killed during shutdown, regardless of whether "resume on restart" or "reboot on restart" was selected. When "reboot on restart" is selected, all processes are marked as "kill on powerfail" by default. Processes go through one of two logical paths during shutdown based on the disposition of the "kill on powerfail" property. After the power failure has been confirmed, processes which have been marked as "kill on powerfail" will receive the SIGTERM signal. Processes not so marked will receive the SIGPWR signal. The signal handlers accept three parameters: the signal number, a code, and a pointer to a sigcontext structure.

Processes not marked for kill on powerfail will be considered first; these processes receive the SIGPWR signal, and are not marked as "kill on powerfail". The handler for the SIGPWR signal should perform any process-specific procedures at this point. The code will be set to PFQUIESCE to differentiate this delivery of the SIGPWR signal from that given during the restart procedure. When the process has completed its process specific procedures, it should suspend further execution by calling a pause utility. This process will then resume execution returning from pause when SIGPWR with a code of PFRESTART is delivered during the restart procedure.

After the SIGPWR handlers have been allowed to execute, all processes ready to execute will be suspended by removing them from the run queue (actually, processes may be left on the run queue but the scheduler may not schedule any processes for further execution). Processes that have suspended awaiting some event have already left the ready state and will, of course, not be considered for execution either. Forcibly suspended processes will not be aware of the mechanism used by the kernel to either suspend or resume their execution, just as processes are unaware of clock interrupts that occur during their execution.

Processes marked for kill on powerfail will now be considered, i.e., the processes which receive the SIGTERM signal with a code of PFQUIESCE, those marked as "kill on powerfail". The code of PFQUIESCE signifies to the process that this signal delivery is related to a power failure and not some other source. The

straightforward thing for such a process to do is to cleanup and terminate. After the SIGTERM handlers have been allowed to execute, the SIGKILL signal will be posted to all such processes.

Considering now processes during the restart procedure 177, only those of the "resume on restart" type are applicable. If "reboot on restart" was chosen, of course, processes which were in existence during the shutdown will not exist, as the system is rebooted with a fresh copy of the operating system.

During the restart procedure, all processes will also receive the SIGPWR signal. The /etc/pfrestart script is executed for an administrator-configurable period of time prior to the delivery of SIGPWR to all user processes. The mechanism for executing the /etc/pfrestart script is delivery of SIGPWR with a code of PFRESTART. The SIGPWR handler will receive a code of PFRESTART, which may be used to differentiate between the SIGPWR signal delivered at shutdown and that delivered at restart. On restart, the handler may initiate such actions as may be germane to the application at hand. This may include such things as refreshing the terminal screen or rolling back any database transactions that were in progress.

#### Init process handling:

The Unix "init" process receives special handling during the powerfail and shutdown procedures. Init is configured to scan the "/etc/inittab" file and execute POWERFAIL or POWERWAIT actions upon receipt of the SIGPWR signal (just prior to time 181) with codes of PFQUIESCE and PFRESTART, respectively. In this way, the administrator may configure shell scripts which will assist in customizing the shutdown or restart to the particular applications at hand.

The init process receives the SIGPWR signal at an administrator-configurable interval prior to all other processes, whether during the shutdown procedure or the restart procedure. This allows the shell scripts to perform functions that may be adversely affected by the additional cleanup activity incurred as the other processes receive the signals.

#### Device State:

Devices such as the I/O processors 26 and 27, like processes, are given opportunity to save and restore state. The device state, like process state, is saved in nonvolatile storage 148 for restoration during the powerfail restart. Devices, however, receive a finer granularity in the notification of the progress of the shutdown or restart. Each device is configured with a "powerfail routine". This routine is called with various codes, signifying the action to be taken.

At the time 174 of powerfail confirmation, the device powerfail routine is called with a code of PFCONFIRM of Figure 16. The device performs any action that is appropriate.

After process execution is halted or "kill on powerfail" processes are killed, the devices are called with a code of PFHALT at time 184. This code indicates that process execution has halted. In particular, the disk driver may infer that no more reads need be processed. All in-progress reads may be queued for resumption during the restart procedure.

Then the device powerfail routine is called with a code of PFQUIESCE at time 185. The device returns from this routine call, the size in bytes of the state to be saved. The powerfail/autorestart procedure then insures that space is reserved in nonvolatile storage equal to this amount for this particular device.

The next call is done with a code of PFDUMP, and an argument which is the address of the save area reserved as described in the previous paragraph. The device is responsible of recopying its state information into the save area. The powerfail/autorestart procedure will then insure the safety of this data.

When power is restored, the device drivers will receive the standard device identification call as received during a normal boot sequence. The powerfail/autorestart procedure uses the information received from this routine to verify that the hardware device configuration has not been modified during the power outage interval.

The device powerfail routines are called with a code of PFINIT. This call is intended to inform the disk driver that it must perform any requisite initializations to restore that part of the essential system state which is stored on the disk.

Then, sequentially for each device, the nonvolatile saved device state is brought into a memory buffer, and the device powerfail routine is called with a code of PFRESTORE and an argument of the address of the memory buffer.

Finally, the device powerfail routine is called with an argument of PFRESTART, indicating that the device may commence normal operation.

Thus, device drivers, like processes, may have state that needs to be saved across the shutdown/restart cycle. This is more likely to be the case with intelligent controllers. Like processes, the powerfail/autorestart

procedure allows each controller to selectively react to the shutdown/restart.

The device drivers that control physical devices must have a powerfail routine. Communication between the kernel and the device drivers regarding the shutdown/restart will be done by calling this routine. In order to provide for optimal scheduling of writes to nonvolatile storage, effort is made to stage device drivers for the flushing of the file system buffer pool, saving kernel memory, and saving device state.

At the time 174 of powerfail confirmation, the powerfail routine of the driver for each device will be called with a command parameter of PFCONFIRM. This is to give indication to the driver that it must prepare to shutdown. For example, an intelligent network controller (that contains code for the session layer) may use this indication to abort or semigracefully close outstanding connections while refusing new connections.

When all process execution is suspended, a second call is made to the powerfail routine of the driver for each device with a command parameter of PFHALT at time 184. The purpose of this call is to indicate to the disk driver that no further reads will be done. All pending reads should be discontinued until the restart procedure. PFHALT is only meaningful to the disk driver, all other drivers will receive it, but need not perform any activity.

Then at time 185 a third call will be made to the device powerfail routine with a parameter of PFQUIESCE. The purpose of this call is to indicate that all cleanup activity carried out by the device should now be complete, and no further such activity attempted. In fact, the device should not modify kernel/user memory other than to perform the dump operation described in the next paragraph. For example, no calls to kern\_malloc or kern\_free should be made after PFQUIESCE. This is because the essential system image is being written to PFDEV, a non-volatile storage area for the essential system. The return value from this call is an indication of the amount of save area that should be allocated for this device in the essential system state saved into PFDEV. A return value of zero implies that no save area is necessary.

The I/O processor state is saved at this point so that the device state as represented in the access validation ram (AVRAM) is properly captured. This AVRAM state is written to PFDEV as a part of the essential system state.

Finally, when a save area was requested by the driver for the device, a fourth call will be made to powerfail with a command parameter of PFDUMP and an argument parameter of the address of the save area in which to dump the device state (as requested by the PFQUIESCE call). The device driver is then responsible for copying its state information into the save area before returning from this call. The format of the information in the save area is device specific and not defined by the kernel, other than overhead information in the save area is device specific and not defined by the kernel, other than overhead information kept by the kernel to identify this area. Drivers for devices which do not contain powerfail partitions aliased by PFDEV should power down their device following completion of the PFDUMP call.

The disk driver is used to write the device dumps to PFDEV. Therefore, the disk driver cannot dump its own state, because this state would need to be read from disk and restored in order to allow the disk to be initially read. The disk driver, because of its critical role, must be handled specially during shutdown, and restart as well.

Certain device drivers may want to make special cases of the two types of shutdown procedure that can occur, "resume on restart" or "reboot on restart". Device dumps are not actually written to disk if the restart type is "reboot on restart", as this state information will not be necessary to the reboot. However, the device driver is not cognizant of this fact. That is, the interaction between restart procedure and the device driver is identical for both "reboot on restart" and "resume on restart". A device driver may determine the type of shutdown in progress by examining a data structure which is accessible in the device driver's address space. The values of the flags indicating the current settings of the kernel powerfail/autorestart procedure switches, as well as the numeric parameters, are included in a file "sys/rolex/pwrfail.h".

Device drivers during restart will now be considered. Device state is restored only for devices designated "resume on restart". If "reboot on restart" was chosen, of course, device state which was in existence during the shutdown will not be restored, as the system is rebooted with a fresh copy of the operating system.

First, the I/O processor state is restored. This state includes the access validation RAM information that represents a portion of the device state. Then the device identification routine is called for each device. Then, the powerfail routine of the driver for each device will be called with a command of PFINIT. This call is intended for the disk driver for disk 148 only. All other drivers may ignore it. At this point, the disk driver initializes itself so the device state for the other device drivers may be read in off the powerfail dump device, PFDEV. Next, the powerfail routine of the driver for each device will be called with a command of PFRESTORE and an argument of the address of the save area requested by the device during shutdown. If no save area was requested for this device by the driver, the argument will be NULL. This call to the

powerfail routine is to reload any state information.

It is important that the device driver merely recapture the state that was saved during shutdown, when the PFRESTORE command is used. The device driver must not make any state transitions beyond the saved state until the PFRESTART command is issued. Successive restart/shutdown/restart cycles may  
 5 require that the PFRESTORE command be issued multiple times, and thus this operation must be idempotent. When all devices have been restored, the powerfail routine will be called again with an argument of PFRESTART. Note that the powerfail routine is called with a command of PFRESTART in lieu of calling the init routine of the device driver, during the restart procedure. At this point the device may resume normal operation, and make state transitions beyond that saved in the shutdown procedure.

10 For devices that have no need to save state during shutdown the PFRESTORE call to the powerfail routine may be ignored. Then the PFRESTART powerfail routine call may be used to reinitialize the device to resume operation. In any case it is important that device operations which may cause state transitions in a nonidempotent manner be performed following PFRESTART and not before that time.

Since the disk driver is used to read in the saved device state from PFDEV, the disk driver cannot save  
 15 or restore its own state. When the PFRESTORE call is made the disk driver must perform any initialization that is required in order that PFDEV be read and written from. For the disk driver, the PFRESTART call will only signify that the reads which were discontinued at PFHALT may now be continued.

It is important to note that drivers can experience two types of powerfail/autorestart procedure restarts. The first type is the when the system actually loses power. All controllers and devices will have experienced  
 20 a reset prior to the autorestart procedure. The second type occurs either on a forced shutdown, or a transient power failure where AC power returns during the shutdown procedure. This second type is termed a "fall through" restart. In this case, disk devices which contain powerfail partitions aliased by PFDEV will not have experienced a reset. The call made to the device powerfail routine with an argument of PFINIT may then be used to properly reset the device in preparation for the powerfail restart.

25  
 Atomicity and Idempotency:

The characteristics of atomicity and idempotency concern the action taken in the presence of restoration of power in the midst of a shutdown, or subsequent power failure during the restart procedure.

30 The shutdown and restart procedures are of sufficient duration (the time periods 175 and 177 of Figure 16) that it is possible that one may attempt to overlap the other; e.g., power may be restored before the shutdown procedure has completed, even though the delay 173 is introduced to rule out short transients in the supply of power. If the shutdown procedure of time period 175 does not complete before power is restored to the system, the shutdown procedure will run to completion anyhow. The restart procedure is  
 35 then immediately initiated at time 176, independent of any operator interaction. The user may see a longer delay in the response of the system using this procedure, but the complicated procedure from powerfail confirmation at 174 until completion at 176 is an atomic event, and will run to completion once initiated.

The shutdown procedure is thus "atomic" in the sense that once initiated, it will run to completion even if AC power is restored to the system during the time period 175 while the shutdown is running. However, at  
 40 the end of the shutdown procedure, at time 176, if AC power has returned, the restart procedure will be initiated immediately. Otherwise, the powerfail/autorestart procedure will turn the batteries off and the system will need a powerup reset to restart via the boot ROMs.

Another likely scenario is that power may fail in the midst of the restart procedure during the time 177. The restart procedure is also atomic in nature, although different from the shutdown procedure. The restart  
 45 procedure may be "rewound" and initiated again at any point prior to which the state of the restarted system deviates from the essential system image stored on nonvolatile media. The essential system image may be reloaded into memory several times without causing damage. However, as soon as process execution is enabled and device activity started, the state of the system has transitioned beyond the stored essential system image.

50 The restart procedure is thus divided into two parts. A nonatomic, idempotent portion 187 prior to the execution of any processes or state change on any device controllers, and an atomic portion 188 when process execution and device activity is restarted. If a commitment has not been made to resume process execution and device activity, the presence of a powerfail indication will not require a shutdown phase 175, but merely a wait for stable AC power to be restored. Powerfail indication 172 and not confirmation 174 is  
 55 the important point here because powerfail indication during the nonatomic portions 187 of the restart procedure will cause yet another wait for the determination of stable AC power. Once a commitment has been made to resume process execution and device activity, all devices must be restarted and then all process execution resumed, even in the presence of a powerfail confirmation 174. If a confirmed power

failure occurs when the restart has completed the atomic action of resuming process execution and device activity, a full shutdown cycle will occur.

The occurrence of a powerfail confirmation 174 during the atomic resumption of process execution and device activity during restart period 177, and the ensuing initiation of a shutdown procedure (period 175  
5 reinstituted) may shorten the total time the battery supply 162 can supply power during the shutdown procedure. It is important that the process/device driver restart interval be as short as possible to avoid the impact of this limitation on an immediately recurring shutdown procedure.

During the idempotent portion 187 of the restart procedure, a power failure will cause the system to immediately lose power, necessitating a powerup reset as mentioned previously. Thus, if the AC power is  
10 unstable, the idempotent portion 187 of the restart procedure may be executed several times before the system is actually restarted. After a power failure, but with AC power restored by the time of completion of the shutdown procedure, the restart procedure begins immediately then is truncated when a second power failure occurs during the idempotent portion.

The atomic portion of the restart procedure is entered following the idempotent portion, at a "commit"  
15 point 186. When the commit point is reached, the restart procedure will run to completion even in the presence of a power failure. At the end of the restart procedure, if a power failure persists, the shutdown procedure will be entered.

The "commit" point thus divides the restart procedure into the two halves, the first being the idempotent portion 187 and the second being the atomic portion 188. The commit point 186 occurs after  
20 each device has received the call with a code of PFRESTORE. The powerfail/autorestart procedure then waits an administrator-configurable time interval to confirm that AC power is stable, and then "commits" to complete the restart. Note that since the AC power confirmation interval logically lies in the idempotent portion of the restart procedure, a power failure during this time will again wait for a powerup reset as  
25 aforementioned.

#### System Administrator:

The system administrator's access to the powerfail/autorestart procedure includes the setting of parameters in the kernel, forcing a system shutdown on demand, shell scripts run at shutdown and restart,  
30 selectively setting a per process "kill on powerfail" property, the creation of the aliased powerfail dump device (PFDEV) and its associated powerfail partitions, and hardware reconfiguration over the duration of a power failure.

The shutdown and restart procedures have certain kernel parameters accessible to the system administrator. For example, the administrator may select the "resume on restart" option, in which case the  
35 operation of the system is resumed essentially where it left off prior to the shutdown. The administrator may otherwise choose the "reboot on restart", which causes the operating system to be rebooted rather than resumed.

Other kernel parameters accessible to the system administrator include: (1) the time interval 173 between powerfail indication and powerfail confirmation (failtime), (2) a ceiling on the number of acceptable  
40 powerfail interrupts in the powerfail indication/confirmation interval 173 (intcnt), (3) the amount of time the battery supply can reliably function when fully charged (uptime), (4) the time interval between powerfail confirmation 174 when the "/etc/pfshutdown" shell script is executed, the time 181 of posting of SIGPWR (processes not possessing the "kill on powerfail" property) or SIGTERM (processes possessing the "kill on powerfail" property) to all user processes; and on restart, the time interval 190 between the execution of the  
45 "/etc/pfrestart" shell script and the posting of SIGPWR to all user processes (pwrtime), (5) the time interval between the posting at 181 of SIGPWR (processes not possessing the "kill on powerfail" property) or SIGTERM (processes possessing the "kill on powerfail" property) to all user processes and suspension of process execution (all processes not possessing the "kill on powerfail" property) or posting at 182 of SIGKILL (all processes possessing the "kill on powerfail" property) to all user processes (termtime), (6) the  
50 action to perform when the battery supply 162, 163 cannot reliably support the duration of a full shutdown procedure (shutact), (7) the amount of time AC power must be restored and stable before initiating the restart procedure (actime), and (7) the action to perform during the boot procedure when it is evident that the battery supply could not support a full shutdown procedure because the batteries have been drained and need recharging (resact).

The system administrator may force a shutdown process, without the occurrence of a power failure, to  
55 load the batteries and insure that they are operational. Forced shutdowns may be done as a part of the administrative routine on a regular interval to insure the reliability of the battery supply. A system call is provided to force a shutdown in a manner similar to that which occurs at the time of a power failure. The

differences between a forced shutdown procedure and an actual powerfail confirmation initiated shutdown include the shutting off of the bulk power supplies, and the initiation of the restart procedure. A forced shutdown shuts off the bulk power supplies, to test the ability of the batteries to supply power. The type of restart procedure is always "resume on restart", if the shutdown is forced. Since the restart procedure will not be triggered by a powerup indication, the forced shutdown procedure software must initiate the restart procedure.

Site or application specific information may be included in one of two shell scripts, /etc/pfshutdown and /etc/pfrestart. The shutdown procedure will execute the /etc/pfshutdown script. The restart procedure executes the /etc/pfrestart script. In these scripts the administrator may perform such maintenance chores as killing all processes associated with a database management system during the shutdown procedure, and restarting the dbms during the restart procedure. These shell scripts are the primary mechanism for administrative tailoring of the functionality of the powerfail/autorestart procedure.

#### Disk System Considerations for Shutdown and Restart:

The disk system 148 contains the powerfail partitions that collectively form the nonvolatile storage area for the essential system image.

The essential system image consists of all process and kernel state that must be saved to allow the restart procedure to function properly. The process state includes the Unix area, data and stack pages, and possibly other information. The process table slot and other system data structure information associated with the process is part of the kernel state. Note that if the "reboot on restart" option is chosen, no essential system state is saved.

If an I/O error occurs when saving the essential system image into the PFDEV, the system will be set to "reboot on restart" regardless of the value of the kernel parameter which requests "resume on restart". The shutdown procedure will be aborted, and device and process state will be lost.

Upon restart, if the "reboot on restart" option is chosen, the disk system 148 will be involved in bringing a new copy of the operating system off from the disk. Rather than pursuing a normal boot when AC power is restored, the essential system image contained on PFDEV is loaded into memory 14, 15 or 16. This essential system image contains device state information which may be passed to a given device, as previously mentioned, and then discarded. The other portion of the essential system state consists of an actual core image, possibly in noncontiguous portions. If an I/O error occurs when restoring the essential system state, control is passed back to the initial boot sequence and a fresh copy of the operating system is loaded, regardless of the value of the kernel parameter which requests "resume on restart".

#### Battery OK signals:

Each battery which makes up the battery supplies 162 and 163 presents a "battery OK" signal via the processor 170 which may be monitored from the CPUs by polling, or through the interrupt that is generated by a transition in this signal. The powerfail/autorestart procedure interprets the battery OK signal presence as signing that a full shutdown can be supported. The duration of a "Full" shutdown is defined by the system administrator. The absence of the battery OK signal is interpreted as implying that the battery cannot support a full shutdown without losing power to the machine as supplied by that battery, or damaging the battery through drastic discharge. For any given module, if a single battery presents the battery OK signal, the module can support a full shutdown. It is not necessary that both batteries 162 and 163 present "battery OK".

The powerfail/autorestart procedure makes use of the battery OK signals in several places. The battery recharge delay done during a normal boot or powerfail/auto restart, will wait until the battery OK signal is presented by at least one battery in each module. During the powerfail shutdown procedure, the shutdown may be aborted if the battery OK signal is not presented by at least one battery.

When AC power is restored, regardless of whether the "reboot on restart" or "resume on restart" option is chosen, a delay may be incurred prior to initiating the boot/resume. This delay allows the batteries 162, 163 to be sufficiently charged so that another power failure can be supported. That is, it is undesirable to bring the system back online when it cannot be execute another orderly shutdown because the batteries are low. The boot procedure will delay for a time interval, based on the amount of time that the shutdown procedure discharged the batteries and the settings of the kernel parameters. The shutdown procedure accumulates the battery discharge time since last recharge and stores this value in nonvolatile storage. The delay time for a full battery charge is, for example, sixty times the discharge time.

## System memory organization:

When the core image portion of the essential system state is written to PFDEV, it is important that each write be as large as possible; it would be preferable to do this in one large write, but the architecture of the system does not allow this possibility. Therefore, it is essential that the global memory 14, 15 include a large "window" which contains no system data structures 144, only user data 145; of course, the larger the size of this "window" in global memory 14, 15, the faster the saving of the core image will be. Then the powerfail/autorestart procedure can write first the data in this "window" from global memory to disk 148. Then the rest of system memory (local and global) can be copied to the "window" in global memory, and from there written to disk 148. In particular, all allocation routines must be precluded from allocating a portion of memory to be used by system anywhere in this "window" which the powerfail/autorestart procedure will use in global memory. The majority of the code which will allocate data structures in global memory is related to the I/O subsystem, into order to accomplish DMA transfers and such.

## Pseudo-code Functionality Summary

The pseudo-code listing set forth in Table A, along with the time line set forth in Table B and associated timing diagram of Figure 16, illustrate the features of one embodiment of the invention as discussed above. The example "time line" of Table B is a typical shutdown and restart, including a single shutdown/restart cycle. This, of course, bypasses scenarios that develop in the presence of aborted and multiple restart attempts. The sequence of actions presented in the time line and Figure 16 is significant. For example, process execution must be suspended prior to flushing the dirty file system buffers, which in turn must be done prior to quiescing and dumping device state. The times presented in the time line, represented in minutes and seconds, are for exemplary purposes only.

## The /config filesystem

To allow user programs to access the current configuration of the system described above, a pseudo filesystem is added, referred to as the /config filesystem. A file exists in /config for each software subsystem and each hardware component in the system. Referring to Figure 17, a tree structure is illustrated for this /config filesystem. A directory listing for /config will always show the true configuration of the system, which is of great importance to a system as shown above where the configuration can change while the system is running.

The hardware subtree 180 of Figure 17 represents the current physical hardware configuration of the system of Figures 1-12. Only the hardware actually present in the system is present as an entry in the /config filesystem. For example, if there is no memory board C (memory module 15 of Figure 1) present in slot C the corresponding node tmrcC will not appear in the tmrc directory. When components are added to or removed from the system the hardware subtree 180 is updated. Within the hardware subtree 180 is a subtree 181 for the CPUs, and under this subtree are three possible files 182, 183 and 184, representing the CPUs 11, 12 and 13, which appear as files /config/hw/cpu/cpuA, /config/hw/cpu/cpuB, etc. Likewise, there is a subtree 185 for the memory modules 14 and 15, where files /config/hw/tmrc/tmrcA and /config/hw/tmrc/tmrcC appear if both memory modules 14 and 15 are present. A subtree 186 for the I/O processors 26 and 27 has subtrees /config/hw/iop/iopO/ and /config/hw/iop/iopI/ for the processors 26 and 27, then each of these has VME controllers 30 which are each represented by a file linked to a .slot file 187 corresponding to the VME slot the controller occupies. For SCSI type controllers there is a single controller which appears as a link in both the iop and the msc directories. When viewed with ls() the links between the controllers appear as hard filesystem links.

The software subtree 190 represents the current software configuration of the system, although the software system components are more nebulous than the analogous hardware components in the hardware subtree 180. Not all of the routines in the system are identified with a particular software component, but there are a number of components which can be treated as a software subsystem and have associated start and stop routines. Some, but not all, may also have subsystem re-initialization and re-integration routines. A major distinction from the hardware subtree is that the software subtree has no replicated components.

## User Interface for /config filesystem:

The /config filesystem is a front end to various kernel modules, and /config provides a mechanism for identifying components of a particular kernel module by name and directing system calls to that kernel

module. /Config is automatically mounted during the boot process, to ensure that it will be available for examination by any /etc/rc startup programs.

The nodes in /config may be treated just like regular files in Unix. All files operations may be attempted, though some are not supported and will return errors. User interface to /config is through standard Unix system calls. A summary of the system call support is set forth in Table C, where the column on the left recites standard Unix calls. The system calls can be made from within custom programs or from any commands which make these system calls (e.g., ls(1)). Most of these operations are performed by opening the desired entity then issuing an ioctl(2) system call; for example, to issue a call to the reintegration subsystem to down cpuB (the CPU 12), the following code is executed:

```
fd = open("/config/hardware/cpu/cpuB", O_RDWR);
ioctl(fd, CCF_DOWN, 0);
```

The nodes in the /config filesystem support common commands, particularly some subset of the ioctl calls defined in the /config filesystem header cfs.h:

20	CF_GETSTATE	get state code (integer)
	CF_PGET	get parameter block
	CF_PSET	set parameter block
	CF_INIT	initialize
	CF_DIAG	run diagnostics
25	CF_DOWN	take unit down
	CF_REINT	reintegrate
	CF_OFFLINE	put offline
	CF_RESET	reset
30	CF_MOVE	move (IOP)
	CF_FAILED	mark as failed
	CF_CTRLINFO	get pdev/ldev info
	CF_CONFIG	get config_file array

35

All nodes support CF\_GETSTATE:

40

```
int state;
ioctl(fd, CF_GETSTATE, &state);
```

45 The meaning of the return code, state, varies from component to component except that a value of zero indicates normal operating state and non-zero indicates otherwise. Other values of state may be defined for particular components.

Kernel Interface:

50

The /config filesystem is intended to be simply a shell which performs all the filesystem operations necessary to provide an illusion of files, but has no direct knowledge of the entities it is displaying. With the use of defprocs key system calls, such as read(), write() and ioctl(), are passed on to other kernel modules. Other kernel modules tie into /config through entries in the /config inode (information node) table.

55



The /config inode table is a linked list of data structures of the type cf\_t:

```

5      typedef struct cf_inode {
          char      *cf_name;      /* ascii name */
          ushort    cf_unitnum;    /* if >=0 && <100, append to cf name */
          ushort    cf_mode;       /* mode for chmod(1) */
10         int      cf_size;        /* size */
          cf_id_t    cf_id;        /* unique ID, first arg for procs */
          cfproc_t   *cf_procs;    /* list of defprocs */
          time_t     cf_ctime;     /* same as in stat.h */
          time_t     cf_mtime;     /* same as in stat.h */
15         /* ... */
          struct cf_inode *cf_next; /* next entry in same hierarchy */
          struct cf_inode *cf_sub;  /* first entry in sub hierarchy */
          struct cf_inode *cf_pard; /* parent directory */
20         struct cf_inode *cf_link; /* list of links */
      } cf_t;

```

Each cf\_t defines a particular file or directory (directory if S\_IFDIR is set in cf\_mode). Together they make up the directory tree structure which the user sees, as illustrated in Figure 17.

When a user issues a system call, /config will either satisfy that request or pass the request on the associated kernel module. Each node has a list of procedures (cf.procs) corresponding to the supported operations: open, close, read, write, attr and ioctl. The first argument passed to a procedure is the value stored in the cf\_id field. This field may contain any value, but will typically store an address or unit number to aid in identifying the target of the system call. The value must be unique. All kernel modules which use /config must perform all add, remove, and update

operations to the /config tree of Figure 17. For the hardware subtree a series of easy-to-use interface routines is available as set forth in Table D. These routines are grouped according to the applicable hardware section. Interface routines for the software subtree are beyond the scope of this application.

An example of an ls() command is set forth in Table E. This table shows selected output from an ls() command.

A program listing for the include file for /config filesystem to create the subtrees of Figure 17 is set forth in Table F.

While the invention has been described with reference to a specific embodiment, the description is not meant to be construed in a limiting sense. Various modifications of the disclosed embodiment, as well as other embodiments of the invention, will be apparent to persons skilled in the art upon reference to this description. It is therefore contemplated that the appended claims will cover any such modifications or embodiments as fall within the true scope of the invention.

TABLE A - PSEUDO-CODE LISTING FOR  
POWERFAIL/AUTORESTART PROCEDURE

5

### POWERFAIL CONFIRMATION

```

confirmation:
10      while (NOT powerfail indication) {
          normal fault tolerant operation;
        }

15      delay (failtime);
        Check bulk status;

        if (dual bulk failure in any given box OR
20          power transitions on any given bulk > intent){
            confirm power failure;
            go to shutdown procedure;
        } else {
25          log transient power failure;
            go to confirmation;
        }

```

### SHUTDOWN PROCEDURE

```

30      shutdown_procedure ()
        {
35          mark pfdev invalid;
            set flag, no further delayed writes;
            call drivers with PFCONFIRM;

            send SIGPWR with code PFCONFIRM to init;
40          /* init will run "/etc/pfshutdown" script */
            delay(pwtime);

            if ("reboot on restart") {
45                mark user processes for kill;
            }
            for (all user processes)
                if ("kill on powerfail") {
50                    send SIGTERM with code PFQUIESCE to process;
                }
        }

```

55

```

    } else {
        send SIGPWR with code PFQUIESCE to process;
    }
5   delay (termtime);
   for (all user processes)
       if ("kill on powerfail") {
           send SIGKILL;
10      }
   suspend process execution;
   call drivers with PFHALT;

15   insure that the file system is completey flushed;

   call drivers with PFQUIESCE;
   save the state of the callout table;

20   save the IOP state;

   call drivers with PFDUMP and write device dump to disk;

25   if ("reboot on restart") {
       validate pfdev header;
       go to cleanup;
   }

30   write system memory to disk;
   write valid pfdev header;

   if (forced shutdown) {
35       test batteries;
   }

cleanup:
40   if (no ac power OR
       forced shutdon with load from disk option) {
       disable batteries;
       reboot system;
45   }
}

```

50

55

RESTART PROCEDURE

```

5      restart_procedure()
      {
          /* idempotent portion */
          reinitialize callout table;
          restore IOP state;
10
          reidentify devices;
          while (some device reports config error) {
              query system console;
15              if ("abort" response) {
                  reboot system;
              } else if ("continue" response) {
                  break out of while;
20              }
          }

          call drivers with PFINTT;

25          read pfdev header;
          if (error OR invalid header) {
              reboot system;
          }
30

          call drivers with PFRESTORE;
          while (some device reports config error) {
              query system console;
35              if ("abort" response) {
                  reboot system;
              } else if ("continue" response) {
40                  break out of while;
              }
          }
      }

45      if (resact configured to not recharge batteries) {
          continue;
      } else if (resact configured for maximum recharge) {
          delay (an amount dependent on the shutdown duration);
50
55

```

```
    } else {  
        while (battery OK signal not present) {  
            delay;  
        }  
    }  
  
    /* nonidempotent portion - committ to restart */  
    update pfdev header to show system image is now invalid;  
  
    restore the callout table with shutdown snapshot;  
    call drivers with PFRESTART;  
    restart scheduling user processes;  
  
    send SIGPWR with PFRESTART to init;  
    /* init will run the "/etc/pfrestart" script */  
    delay (pwrttime);  
  
    send SIGPWR with code PFRESTART to all user processes;  
}
```

TABLE B - SHUTDOWN AND RESTART TIMELINES

5

## Sample shutdown timeline:

10	0:00	Powerfail indication at 172. Begin time interval 173 screening out spurious powerfail interrupts.
15	0:05	Powerfail confirmation at 174, power failure condition has persisted. Devices sent PFCONFIRM message. The /etc/pfshutdown script executed. Commence flushing dirty file system buffers. Force all further delayed writes into synchronous writes.
20		
25	0:25	Processes not marked for kill on powerfail sent SIGPWR signal with PFQUIESCE message at 182. Processes marked for kill on powerfail sent SIGTERM signal with PFQUIESCE.
30	0:55	Processes marked for kill on powerfail sent SIGKILL signal.
35	0:57	Process execution suspended. Devices sent PFHALT message. Delay for file system flush completion.
40	1:00	Devices sent PFQUIESCE/PFDUMP messages. I/O processor 26 and 27 state is saved. Essential device state is moved onto PFDEV.
45	1:05	Devices which do not contain powerfail partitions aliased by PFDEV are powered down. Commence saving of essential system state onto PFDEV.

50

55

3:30 Essential system state saved onto PFDEV. Write valid header to PFDEV. System shutdown complete. Remaining devices powered down. Battery supplies 162, 163 sent message to turn off batteries.

4:30 Battery supplies cease reliable operation if batteries are not turned off.

Sample restart timeline:

0:00 AC power restored. Begin time interval to insure AC power is stable.

1:00 AC power is stable. UPS indicates batteries at least minimally charged. System boots and begins loading essential system image.

1:30 IOPs state is restored. Devices are "id"ed, verifying device configuration. Device drivers receive PFINIT message. Device drivers receive PFRESTORE message. Essential device state is restored.

1:35 Commit to restart. Invalidate PFDEV header. Device drivers receive PFRESTART message. Process execution removed. /etc/pfrestart script is executed.

1:55 Processes receive SIGPWR signal with PFrestart argument.

TABLE C

System Call	Action	
open	RONLY RDWR	everyone su only
read/write	†	
stat/fstat	st_dav st_ino st_mode st_nlink st_uid st_gid st_rdev st_size st_atime st_mtime st_ctime	= maj/min of/config <sup>‡</sup> = inode number in filesystem = † = number of links = always zero (root) = always zero (root) = always zero = † = always current time = † = †
ioctl	†	
chmod	†	
access	IRead IWrite IEXEC	everyone su only IFDIR everyone
mount	filesystem remounted	
umount	filesystem unmounted	
statfs	f_fstyp f_bsize f_frsize f_blocks f_bfree f_files f_ffree f_fname f_fpack	= filesystem type number <sup>‡</sup> = 1024 = 0 = 0 = 0 = 0 = 0 = "/config" = "/config"
chown	returns EINVAL	
creat	returns EINVAL	
link	returns EINVAL	
rename	returns EINVAL	
unlink	returns EINVAL	
fcntl	default commands are transparent others return EINVAL	
close	†	
dup	transparent_fs is not notified	
tseek	transparent_fs is not notified	
utime	transparent_fs is not notified	

Note: †action is defined by subtree code.  
‡determined dynamically at boot time.

Items marked with a (†) in the above table indicate that the action is not performed by/config, but is passed through.



TABLE D

5

CPU routines

10

cf\_cpu\_add:

cf\_cpu\_add(unit)

15

int unit;

Add cpu unit to the tree.

20

cf\_cpu\_rm:

cf\_cpu\_rm(unit)

25

int unit;

Remove cpu unit from the tree.

30

TMRC routines

35

cf\_tmrc\_add:

cf\_tmrc\_add(unit)

int unit;

40

Add tmrc unit to the tree.

cf\_tmrc\_rm:

45

cf\_tmrc\_rm(unit)

int unit;

Remove tmrc unit from the tree.

50

55

IOP routines

5           **cf\_iop\_add:**  
               **cf\_iop\_add(unit)**  
               **int unit;**

10           Create a new iop in the directory/config/hw/iop and add the eight slot entries.

**cf\_iop\_rm:**  
 15           **cf\_iop\_rm(unit)**  
               **int unit;**  
               Remove iop unit, all sub-units, and any msc links.

20           **cf\_iop\_state:**  
               **cf\_iop\_state(unit,state)**  
 25           **int unit, state;**  
               Change the state of the unit. State is (0) for failed, (1) for normal.

30

Controller routines

35           **cf\_ctlr\_add:**  
               **cf\_ctlr\_add(pd)**  
               **pdev\_t \*pd;**

40           Create a link to the node:  
                   /config/hw/iop/iop<sub>n</sub>/slot<sub>m</sub>

45           All information is taken from the structure pointed to by **pd** (iop/slot number, ascii name, and unit number).

50

55

cf\_ctlr\_rm:

cf\_ctlr\_rm(pd)

5

pdev\_t \*pd;

Remove the controller node, any subdevices, and msc links.

10

cf\_ctlr\_move:

cf\_ctlr\_move(pd)

pdev\_t \*pd;

15

Move the controller and any local devices to iop<sup>1</sup>. The id fields of the controller and ldevs are updated to reflect the new iop number.

20

cf\_ctlr\_state:

cf\_ctlr\_state(pd, state)

pdev\_t \*pd;

25

int state;

Set state of controller. State is (0) for failed, (1) for normal.

30

### Local Device routines

35

cf\_ldev\_add:

cf\_ldev\_add(pd, subunit, name, appendunit)

pdev\_t \*pd;

40

int subunit;

char \*name;

int appendunit;

45

Create or rename a node in the /config filesystem in the directory:

/config/hw/iop/iop<sub>n</sub>/controller

50

55

The argument **pd** determines iop/iop<sub>n</sub> and controller. **Subunit** is an integer index indicating the sub-unit being created. **Name** is the ascii name which is to be displayed in /config. Only the pointer to the name is saved-space must be allocated by the device driver. If **appendunit** is non-zero the sub-unit number will be appended to the ascii name (handy for names like: port0, port1, port2, ...). If the node already exists only the ascii name will be changed.

**cf\_ldev\_rm:**

```
cf_ldev_rm(pd, subunit)
pdev_t *pd;
int subunit;
```

Remove local device from /config.

**cf\_ldev\_state:**

```
cf_ldev_state(pd, subunit, state)
pdev_t *pd;
int subunit, state;
```

Set the state of a local device. State is (0) for failed, (1) for normal.

### MSC routines

**cf\_msc\_add:**

```
cf_msc_add(unit)
int unit;
```

Add msc unit and the independent bus nodes **mcb0** and **mcb1**.

cf\_msc\_rm:

cf\_msc\_rm(unit)

5

int unit;

Remove msc unit and all sub-nodes.

10

cf\_msc\_link:

cf\_msc\_link(unit,pd)

int unit;

15

pdev\_t \*pd;

Link the controller specified by pd to msc unit.

20

cf\_mscenv\_add:

cf\_mscenv\_add(unit,component)

int unit, component;

25

Add environmental component to msc unit. Component is a code from cfs.h indicating: fans, batteries, bulks.

30

cf\_mscenv\_rm:

cf\_mscenv\_rm(unit,component)

int unit, component;

35

Remove environmental component from msc unit.

40

cf\_mscenv\_state:

cf\_mscenv\_state(unit,component,state)

int unit, component, state;

45

Change the state of an environmental component. State is (0) for failed, (1) for normal.

50

55

Environ Routines

5           **cf\_environ\_add:**  
               **cf\_environ\_add(component)**  
               **int unit;**  
 10           Add main-cabinet environmental component. **Component** is a code from cfs.h  
               indicating: fans, batteries, bulks.

15           **cf\_environ\_rm:**  
               **cf\_msc\_rm(component)**  
               **int unit;**  
 20           Remove main-cabinet environmental component.

25           **cf\_environ\_state:**  
               **cf\_environ\_state(component,state)**  
               **int unit, component, state;**  
 30           Change the state of a main-cabinet environmental component. **State** is (0) for  
               failed, (1) for normal.

35

Low Level Routines

All of the previous interface routines are built using the three low level routines.

40

**cf\_newnode:**  
               **cf\_t \***  
               **cf\_newnode(parid)**  
               **cf\_id\_t parid;**  
 45           Create a new node under the directory indicated by **parid**. All fields in the  
               returned structure must be filled in by hand.  
 50

55

cf\_linknode:

cf\_t \*

cf\_linknode(parid,srcnode)

cf\_id\_t parid;

Create a hard link to node **srcnode** under the directory indicated by **parid**. All fields in the returned structure must be filled in by hand.

cf\_disposenode:

cf\_disposenode(id)

cf\_id\_t id;

Remove node indicated by **id** from the tree. All children and all links are also removed.

Miscellaneous:

cf\_findid:

cf\_t \*

cf\_findid(id)

cf\_id\_t id;

Return the node whose **df\_id** field matches **id**.

TABLE E

Component	mode bits	Size	State
cpu	---x--x--x	mem size	NORMAL
	-----		DEAD
	-----T		REINTABLE
	(no entry)		ABSENT
tmrc	-rwxrwxrwx	mem size	NORMAL, primary
	-rw-rw-rw-	mem size	NORMAL, backup
	--w--w--w-	reint progress	REVIVE
	-----		OFFLINE
iop	(no entry)		ABSENT
	d--x--x--x		NORMAL
	d-----		OFFLINE
	(no entry)		ABSENT
ctrl	d--x--x--x		OK (with subdevices)
	d-----		not-OK (with subdevices)
	---x--x--x		OK (no subdevices)
	-----		not-OK (no subdevices)
subdev	(no entry)		ABSENT
	---x--x--x		OK
	(no entry)		ABSENT
	---x--x--x		NORMAL
fan	-----		FAILED
	(no entry)		ABSENT
	---x--x--x		NORMAL
	-----		FAILED
battery	---x--x--x		NORMAL
	-----		FAILED



## TABLE F

5

```

10
11 /*
12  * cfs.h - include file for /config file system
13  */
14 #ifndef _sys_fs_cfs.h
15 #define _sys_fs_cfs.h
16
17 typedef unsigned long cf_id_t; /* size of unique id field */
18
19 /*
20  * defproc structure -- each node in /config has a pointer to one of these.
21  */
22 typedef struct cfproc {
23     int      (*cf_openproc)(); /* called on first open of inode */
24     int      (*cf_closeproc)(); /* called on last close of inode */
25     int      (*cf_readproc)(); /* called on read inode */
26     int      (*cf_writeproc)(); /* called on write inode */
27     int      (*cf_attrproc)(); /* called on attr change (e.g. chmod, chown)
28     int      (*cf_ioctlproc)(); /* called on ioctl() */
29 } cfproc_t;
30
31 /*
32  * config inode -- directory or plain file
33  */
34 typedef struct cf_inode {
35     char      *cf_name; /* ascii name */
36     ushort    cf_unitnum; /* if >=0 && <100, appended to cf_name */
37     ushort    cf_mode; /* mode for stat(2) */
38     int       cf_size; /* size */
39     cf_id_t    cf_id; /* unique ID, first arg for procs */
40     cfproc_t *cf_procs; /* list of defprocs */
41     time_t    cf_ctime; /* same as in stat.h */
42     time_t    cf_mtime; /* same as in stat.h */
43     /* ... */
44     struct cf_inode *cf_next; /* next entry in same hierarchy */
45     struct cf_inode *cf_sub; /* first entry in sub directory */
46     struct cf_inode *cf_pard; /* parent directory */
47     struct cf_inode *cf_link; /* list of links */
48 } cf_t;
49
50 extern cf_t *cf_addnode(), *cf_linknode(), *cf_findid();
51
52 /* ioctl's common to all /config entities */
53 #define CFCODE ('c'<<8)
54 #define CF_GETSTATE (CFCODE|00) /* get state code (integer) */
55 #define CF_PGET (CFCODE|01) /* get parameter block */
56 #define CF_PSET (CFCODE|02) /* set parameter block */
57 #define CF_INIT (CFCODE|03)
58 #define CF_DIAG (CFCODE|04)
59 #define CF_DOWN (CFCODE|05)
60 #define CF_REINT (CFCODE|06)

```

55

TABLE F (Cont'd)

```

5.
61 #define CF_OFFLINE    (CFCODE|07)
62 #define CF_RESET      (CFCODE|010)
63 #define CF_MOVE       (CFCODE|011)
64 #define CF_FAILED     (CFCODE|012)
10 65 #define CF_CTRLINFO  (CFCODE|013)    /* get pdev/ldev info */
66 #define CF_CONFIG     (CFCODE|014)    /* get config_file array */
67
68
69 /*
70  * IDs for the /config/hw branch are formed as follows:
15 71  * -----
72  * | 0 | board type | board # | slot |          subdev          |
73  * -----
74  * 1bit   7 bits      4 bits   4 bits      16 bits
75  *
76  * The high bit is always zero.
20 77 */
78
79 /* make id from board type, board num, slot, and subdev */
80 #define MKID(bt,bn,s,sd) (((bt) & 0x7F) << 24) | (((bn) & 0xF) << 20) |
81                        (((s) & 0xF) << 16) | ((sd) & 0xFFFF))
82
25 83 /* get board type, board num, slot, and subdev from id */
84 #define ID_TO_BRDTYPE(id) (((id) >> 24) & 0xFF)
85 #define ID_TO_BRDNUM(id)  (((id) >> 20) & 0xF)
86 #define ID_TO_SLOT(id)   (((id) >> 16) & 0xF)
87 #define ID_TO_SUBDEV(id) ((id) & 0xFFFF)
88
30 89 #define INVALID_BRD      0xF
90 #define INVALID_SLOT     0xF
91 #define INVALID_SUBDEV   0xFFFF
92
93 /* board types */
35 94 #define CPU_TYPE         1
95 #define THRC_TYPE        2
96 #define IOP_TYPE         3
97 #define ENVIRON_TYPE     4    /* batteries, fans, prereqs */
98 #define ENVIRON_BATT     0    /* unit offset */
99 #define ENVIRON_FAN      2
40 100 #define ENVIRON_BULK    5
101 #define MSC_TYPE         5
102
103 #define CPUDIR    MKID(CPU_TYPE,-1,-1,-1)    /* cpu directory */
104 #define CPUA     MKID(CPU_TYPE,0,-1,-1)
105 #define CPUB     MKID(CPU_TYPE,1,-1,-1)
45 106 #define CPUC     MKID(CPU_TYPE,2,-1,-1)
107 #define THRCDIR  MKID(THRC_TYPE,-1,-1,-1)    /* tmrc directory */
108 #define THRCA    MKID(THRC_TYPE,0,-1,-1)
109 #define THRCC    MKID(THRC_TYPE,1,-1,-1)
110 #define IOPDIR   MKID(IOP_TYPE,-1,-1,-1)     /* iop directory */
111 #define IOP0     MKID(IOP_TYPE,0,-1,-1)
50 112 #define IOP1     MKID(IOP_TYPE,1,-1,-1)
113 #define IOP2     MKID(IOP_TYPE,2,-1,-1)
114 #define IOP3     MKID(IOP_TYPE,3,-1,-1)
115 #define ENVDIR   MKID(ENVIRON_TYPE,-1,-1,-1) /* environ directory */
116 #define MSCDIR   MKID(MSC_TYPE,-1,-1,-1)     /* msc directory */
117 #define MSC0     MKID(MSC_TYPE,0,-1,-1)
55 118
119 #endif _sys_is_cis.h

```

## Claims

- 5 1. A method of operating a computer system having multiple CPUs executing the same instruction stream the CPUs each having local memory and also each accessing multiple global memory units storing identical data comprising the steps of:
  - a) detecting an error in one of said CPUs;
  - 10 b) isolating said one CPU from the system and continuing to execute said instruction stream and accessing said global memory units by the other ones of said CPUs;
  - c) reintegrating said one CPU after rendering said CPU operative by first bringing said one CPU into sync with the said other ones of said CPUs, then restoring the state and the local memory of said one CPU to be identical to the state and the local memory of the said other ones of the CPUs.
- 15 2. A method according to claim 1 wherein there are three said CPUs and two said global memory units, and wherein any one of the global memory units may be designated as primary for the purpose of supplying read data to said multiple CPUs and the other of the said global memory units is designated as a backup.
- 20 3. A method according to claim 1 wherein said step of restoring the state and the local memory includes:
  - a) copying each state variable of the other ones of the CPUs to global memory and then copying each state variable from global memory to the appropriate state register in all of said multiple CPUs;
  - b) copying a portion of local memory of the other ones of the CPUs to global memory and then copying said portion from global memory to local memory in all of said multiple CPUs;
  - 25 c) repeating step b) for different portions of local memory of the other ones of the CPUs until all variables stored in local memory of the other ones of the CPUs has been copied to global memory and then copied from global memory to all of said multiple CPUs.
- 30 4. A method according to claim 1 including the steps of:
  - a) removing said one CPU from said computer system without shutdown of said system and while the other ones of the CPUs continue execution of said instruction stream;
  - b) replacing said one CPU in said computer system also without shutdown and while instruction execution continues.
- 35 5. A method according to claim 1 comprising the steps of:
  - a) detecting an error in one of said global memory units;
  - b) isolating said one of said global memory units and continuing to execute said instruction stream and accessing a remaining global memory unit of said global memory units;
  - c) reintegrating said one global memory unit by restoring the state and memory contents of said global memory unit to be identical to the state and memory contents of the said other ones of the global memory units;
  - 40 d) and thereafter continuing to execute said instruction stream accessing said multiple global memory units including said one global memory unit.
- 45 6. A method according to claim 5 wherein said step of restoring the state and the memory contents of global memory includes:
  - a) configuring said one global memory unit to ignore all access requests from I/O Processors;
  - b) reading each global memory unit state variable from the primary global memory unit to said multiple CPUs and storing said state variable from the multiple CPUs to all global memory units including said global memory unit;
  - 50 c) reading each data word stored in the primary global memory unit to said multiple CPUs and storing said data word from the multiple CPUs to all global memory units including said global memory unit;
  - d) configuring said one global memory unit to execute all access requests from I/O Processors;
  - 55 e) repeating step c.
7. A method according to claim 5 wherein there are two said global memory units either one of which is designated primary and the other is designated as a backup, and including the step of changing the

designations of the global memory units if an error is detected in the global memory unit previously designated as primary.

8. A method according to claim 5 wherein said steps of reading each global memory unit state variable and reading each data word stored in global memory includes checking the validity of the data in each of said multiple global memory units.
9. A fault-tolerant computer system, comprising:
  - a) first, second and third CPUs of substantially identical configuration each having local memory, said first, second and third CPUs executing substantially the same instruction stream;
  - b) first and second global memory modules of substantially identical configuration, said first and second memory modules storing substantially the same data;
  - c) busses coupling each of the first, second and third CPUs individually to each of said first and second global memory modules whereby said first, second and third CPUs access said first and second global memory modules separately and in duplicate;
  - d) said CPUs continuing to execute said instruction stream even though one of said first, second and third CPUs is inoperative and continuing to access one of said first and second global memory modules even though the other is inoperative;
  - e) said one of said first, second and third CPUs which is inoperative being replaceable into the system without shutdown of the system while the other ones of said CPUs continue execution of said instruction stream;
  - f) said one of said first, second and third CPUs which is inoperative being rendered operative and restored to normal function in the system without shutdown of the system while the other ones of said CPUs continue execution of said instruction stream;
  - g) said other of the global memory modules which is inoperative being replaceable into the system without shutdown of the system while said first, second and third CPUs continue to access the global memory module which is operative;
  - h) said other of the global memory modules which is inoperative being rendered operative and restored to normal function in the system without shutdown of the system while said first, second and third CPUs continue to access the global memory module which is operative.
10. A system according to claim 9 further including:
  - i) a first input/output bus coupled to said first global memory module and a second input/output bus coupled to said second global memory module; and
  - j) a first input/output processor coupled to both said first and second input/output busses, and a second input/output processor coupled to both said first and second input/output busses.
11. A system according to claim 10 further including:
  - k) one I/O bus coupled to said first input/output processor and a second I/O bus coupled to said second input/output processor;
  - l) one or more Bus Interface Modules coupled to both said first and second I/O busses
  - m) one I/O Controller coupled to each Bus Interface Module
  - n) one or more I/O devices coupled to each I/O Controller.
12. A system according to claim 9 wherein said first, second and third CPUs are operating on independent clocks so that said execution is asynchronous; and wherein said first, second and third CPUs are loosely synchronized upon the event of a reference to the global memory modules by detecting an access to said first and second global memory modules and stalling any CPUs for which the access occurs earlier to wait until the last one of said CPUs executes said access, then allowing the access to occur.
13. A system according to claim 9 wherein either of said global memory modules is designated as primary and the other is designated backup, and wherein write operations by the CPUs are executed in both of said global memory modules but in read operations said CPUs received data from only the primary global memory module; and wherein the backup global memory module may be designated primary and the primary may be designated backup, at any time.
14. A system according to claim 12 wherein said global memory module include means for voting said

references to said global memory modules, and wherein data is voted only for writes in said means for voting said references to said global memory modules, and addresses and commands are voted for both read and write references to said global memory modules.

- 5 15. A system according to claim 11 wherein;
  - a) each said I/O controller is assigned to one of the two said input/output processors coupled via said I/O bus and said Bus Interface Module; and
  - b) each input/output processor coordinates global memory accesses for its assigned I/O controllers; and
  - 10 c) each input/output processor monitors said assigned I/O Controllers for incorrect behavior and reports hard and soft errors to the CPUs via interrupts.
16. A system according to claim 15 wherein a faulty input/output processor can be isolated, held in a Reset state, and its assigned I/O Controllers reassigned to the other input/output processor which is coupled to the said I/O Controllers.
- 15 17. A system according to claim 11 wherein a faulty I/O Controller can be isolated, held in reset, and powered down until said I/O Controller is removed and replaced; and wherein a faulty disk drive module attached to an I/O Controller can be isolated and powered down until said disk drive is removed and replaced.
- 20 18. A system according to claim 11 comprising means for detecting an error in one of said input/output processors; and wherein all I/O Controllers assigned to said input/output processor are reassigned on detection of an error to the other input/output processor which is coupled to the said I/O Controllers; and wherein the faulty input/output processor is isolated from the system without system shutdown and continuing normal system operation using said other input/output processor while said faulty input/output processor is replaced in the system and is rendered operative by restoring its state; and wherein the I/O Controllers are reassigned to the said input/output processor.
- 25 19. A system according to claim 17 comprising means for detecting an error in a disk drive module for isolating and powering down said disk drive module; wherein normal system operation continues using a mirror or equivalent for said disk drive module while said disk drive module is replaced in the system without system shutdown; and wherein the replaced disk drive module is rendered operative by restoring its state to be substantially identical to its mirror or equivalent.
- 30 20. A system according to claim 17 comprising: means for detecting an error in one of said I/O controllers for isolating said I/O Controller from the system without system shutdown by removing power from said I/O controller; and wherein said I/O Controller can be replaced in the system without system shutdown by rendering said I/O controller operative by restoring its power, restoring its state and reestablishing the operating states for all I/O devices attached to said I/O Controller.
- 35 21. A system according to claim 11 further including:
  - o) dual power subsystems providing normal operational power for the redundant modules in the systems such that normal system operation can continue in the event of a failure of one power subsystem component;
  - 45 p) dual battery backup power subsystems providing sufficient power to allow graceful shutdown of the system in the event of a loss of mains power even when one of said battery backup power subsystems is inoperative;
  - q) redundant cooling systems with cooling efficiency sensors on each cooling module such that the efficiency of all remaining cooling modules can be increased to compensate for a faulty cooling module.
  - 50
22. A system according to claim 21 comprising:
  - means for detecting an error in one of said cooling modules; wherein said one of said cooling modules can be removed without system shutdown and while normal system operation continues for replacement of said cooling module without system shutdown and while normal system operation continues.
  - 55
23. A method of operating a computer system including the steps of:

- a) executing the same instruction stream in first, second and third CPUs;
  - b) generating global memory accesses in each of said first, second and third CPUs at separate first, second and third global memory access busses;
  - c) storing duplicative data in first and second global memory modules having substantially identical address spaces within the address range of said CPUs, including executing accesses to each one of said first and second global memory modules via said first, second and third global memory access busses;
  - d) voting each one of said accesses in said first and second global memory modules when received from said first, second and third global memory access busses, said voting including comparing information representing said accesses;
  - e) allowing said accesses to be completed only where at least two of said global memory access busses present the same such information;
  - f) placing offline one of said first, second and third CPUs when a global memory access from said one is different from the other two upon said voting, then placing said one CPU back online without shutdown of the system after said one of the CPUs is rendered operative.
24. A method according to claim 23 including the step of placing offline one of said first and second global memory modules when an error is detected in global memory access, then replacing said one of said global memory modules into the system without shutdown of the system after said one of the global memory modules is rendered operative.
25. A method according to claim 23 including the step of synchronizing said first, second and third CPUs whereby said CPUs are substantially simultaneously executing the same instruction stream, and wherein said step of synchronizing said CPUs includes stalling execution of global memory accesses until all three of the first, second and third CPUs are executing the same global memory access at the same time; and wherein said step of synchronizing also includes timing the implementation of external interrupts of the CPUs so that all three of the first, second and third CPUs are executing the same instruction at the time the interrupt is presented.
26. A method of operating a computer system comprising the steps of:
- a) executing code by a CPU from memory, including page swapping from said memory and file access to non-volatile storage, in normal operation;
  - b) detecting a failure of a power supply for said system and initiating a shutdown process in response thereto, said shutdown process including switching to backup power;
  - c) said shutdown procedure including storing the state of said computer system including the state of processes being executed, in said non-volatile storage;
  - d) after completing said shutdown procedure, if said power supply has been restored, initiating a restart procedure;
  - e) said restart procedure including reading said stored state from said non-volatile storage and restarting said processes and continuing execution without rebooting;
  - g) or, if said power supply has not been restored, shutting down said backup power and ceasing execution by said CPU.
27. A method according to claim 26 wherein said shutdown procedure is completed even though said power supply has been restored before the shutdown procedure is completed; and wherein said step of detecting said failure of said power supply includes waiting for a time period after receiving an indication of said failure to determine if said failure is merely a transient, before said initiating said shutdown process.
28. A method according to claim 26 wherein said step of executing code by said CPU includes delayed writes to said non-volatile storage, and said shutdown procedure includes executing all pending delayed writes and initiating no new delayed writes.
29. A method according to claim 26 including the steps of detecting another failure of said power supply, said restart procedure terminating if said another failure occurs before a selected time delay, said restart procedure continuing to completion if said another failure occurs after said selected time delay.
30. A method according to claim 26 wherein said power supply is AC line power and said backup power

supply is a battery; and wherein said nonvolatile memory is disk memory.

31. A method of operating a computer system comprising the steps of:
  - a) detecting a failure of a power supply for said system and initiating a shutdown process in response thereto, said shutdown process including switching to backup power;
  - b) continuing said shutdown process to completion using said backup power even if said power supply is restored before said completion;
  - c) after said shutdown process is completed, beginning a restart process for said computer system if said power supply is restored while detecting another failure of said power supply if it occurs, said restart process terminating if said another failure occurs before a selected time delay, said restart process continuing to completion if said another failure occurs after said selected time delay;
  - d) after said shutdown process is completed, turning off said backup power if said power supply has not been restored.
32. A method according to claim 31 wherein said power supply is AC line power and said backup power supply is a battery; wherein said shutdown process includes writing to nonvolatile memory the state of processes executing on said computer system; and wherein said nonvolatile memory is disk memory.
33. A method according to claim 31 wherein said restart process does not reboot said computer system but instead restores the state existing before said shutdown process.
34. A method according to claim 31 wherein said step of detecting said failure of said power supply includes waiting for a time period after receiving an indication of said failure to determine if said failure is merely a transient, before said initiating said shutdown process; and wherein said shutdown process includes the steps of writing state information of a CPU, processes and devices of said system to selected locations in volatile memory then writing said selected locations to non-volatile memory.
35. A method of operating a computer system comprising the steps of:
  - a) executing a process using memory for delayed writes of files usually stored on disk;
  - b) detecting a failure of a power supply for said computer system;
  - c) entering a shutdown procedure using backup power including writing to disk all pending delayed writes and issuing no additional delayed writes, said shutdown procedure including storing state of said process to disk;
  - d) completing said shutdown procedure even if said power supply is restored during executing of said shutdown procedure.
36. A method according to claim 35 wherein said shutdown process includes the steps of writing state information of a CPU, processes and devices of said system to selected locations in volatile memory then writing said selected locations to disk.
37. A method of operating a computer system comprising the steps of:
  - a) executing code by a CPU from a memory in normal operation, said execution including calls to a device;
  - b) detecting occurrence of failure of a power supply for said system, and continuing execution of code by said CPU using backup power;
  - c) initiating execution of a shutdown procedure by said CPU, including issuing a sequence of device calls to said device, while continuing execution of said shutdown procedure by the CPU to save state of processes being executed, the device calls including:
    - i) a first device call indicating powerfail;
    - ii) a second device call indicating halt of further device operations;
    - iii) a third device call indicating the amount of memory needed by the device to save state;
    - iv) a fourth device call including an address in said memory to save state of said device;
  - d) storing on disk the data written by said device to said address in memory; and
  - e) shutting down said backup power and ceasing execution of code by said CPU.
38. A method according to claim 37 including the steps of:
  - a) detecting restoration of said power supply;
  - b) initiating execution of a startup procedure by said CPU, including issuing another sequence of

device calls to said device, including:

- i) a fifth device call to initialize the device and return device configuration;
- ii) a sixth device call to initiate loading state for said device from said memory, said state having been read from disk to memory; and
- iii) a seventh device call to initiate normal operation of said device.

39. A method of operating a computer system comprising the steps of:

- a) executing code by a CPU from a memory in normal operation, said execution including signals to processes;
- b) detecting occurrence of failure of a power supply for said system, and continuing execution of code by said CPU using backup power;
- c) initiating execution of a shutdown procedure by said CPU, including issuing a sequence of signals to processes, while continuing execution of said shutdown procedure by the CPU to save state of processes being executed, the signals to processes including:

- i) **SIGPWR with code PFQUIESCE during shutdown followed by SIGPWR with code PFRESTART, or**
- ii) **SIGTERM with code PFQUIESCE followed by SIGKILL;**

- d) storing on disk said state; and
- e) shutting down said backup power and ceasing execution of code by said CPU;
- f) and including the step of marking a process for kill on powerfail.

40. A method of operating a computer system, the computer system including multiple units including at least one CPU unit, at least one memory unit, and at least one I/O unit, comprising the steps of: creating a filesystem having a directory tree with an entry for each said multiple units; removing at least one of said multiple units from said system, and correspondingly removing said entry therefor from said filesystem; replacing said removed unit in said system while said system is continuing to operate, and replacing said entry in said filesystem for the replaced unit.

41. A method according to claim 40 including the step of executing an instruction stream by said at least one CPU unit, including executing a Unix operating system; and wherein said filesystem includes a subdirectory for CPU units and an individual file for each of said at least one CPU units, and includes a subdirectory for memory units and an individual file for each one of said at least one memory unit.

42. A method of operating a computer system, comprising the steps of:

- executing the same instruction stream by a plurality of CPU units; accessing by said CPU units a plurality of memory units storing the same data and a plurality of redundant I/O units;
- creating a filesystem having a directory tree with an entry for each of said CPU units, each of said memory units and each of said I/O units;
- removing at least one of said CPU units, or at least one of said memory units, or at least one of said I/O units from said system, and correspondingly removing said entry therefor from said filesystem;
- replacing said removed CPU unit, memory unit or I/O unit in said system while said CPU units are continuing to execute said instruction stream, and replacing said entry in said filesystem for the replaced unit.

43. A method according to claim 42 wherein there are three of said CPU units; wherein there are two of said memory units; wherein there are at least two of said I/O units; and wherein said step of executing an instruction stream includes executing a Unix operating system.

44. A computer system comprising:

- a) first, second and third CPU units executing the same instruction stream, each of said CPU units having a separate memory access port, wherein when one of said first, second and third CPU units fails, said one is placed off-line and the remaining two continue to execute said instruction stream;
- b) first and second memory units having identical address spaces within the address range of said



CPU units for storing duplicative data, each one of said first and second memory units having first, second and third input/output ports coupled to said memory access ports of said first, second and third CPU units, respectively, wherein when one of said first and second memory units fails, said one is placed off-line and the remaining memory unit continues to be accessed by said CPU units;

c) a file system storing a directory having an entry for each one of said CPU units and memory units unless a respective one of said CPU units or memory units is off-line.

45. A system according to claim 44 wherein each one of said memory units has first, second and third ports to said CPU units, said ports including voting means to compare information between the ports for accesses and to allow accesses to be completed only where at least two of the ports have the same such information for each of the memory units; and including first and second input/output busses, and wherein said first and second memory means each has a separate peripheral I/O port, and said first and second input/output busses are separately coupled to said I/O ports of said first and second memory means; and including means for synchronizing execution of the instruction stream in said CPU units by stalling execution of a memory reference until all three of said first, second and third CPU units are executing the exact same memory reference.

46. A system according to claim 44 wherein each one of said CPU units has a separate clock whereby said CPU units operate asynchronously; wherein each one of said first and second memory units has a separate clock, whereby said CPU units and memory units all operate asynchronously; and wherein said CPU units are loosely synchronized with one another by stalling leading CPU units until the slower CPU units have caught up, upon the event of a memory reference.

47. A fault-tolerant computer system, comprising:

a) first, second and third CPU units of substantially identical configuration, said first, second and third CPUs executing substantially the same instruction stream, wherein when one of said first, second and third CPUs fails, said one is placed off-line and the remaining two continue to execute said instruction stream;

b) first and second memory units of substantially identical configuration, said first and second memory units storing substantially the same data, wherein when one of said memory units fails said one is placed off-line;

c) busses coupling each of the first, second and third CPU units individually to each of said first and second memory units whereby said first, second and third CPU units access said first and second memory units separately and in duplicate;

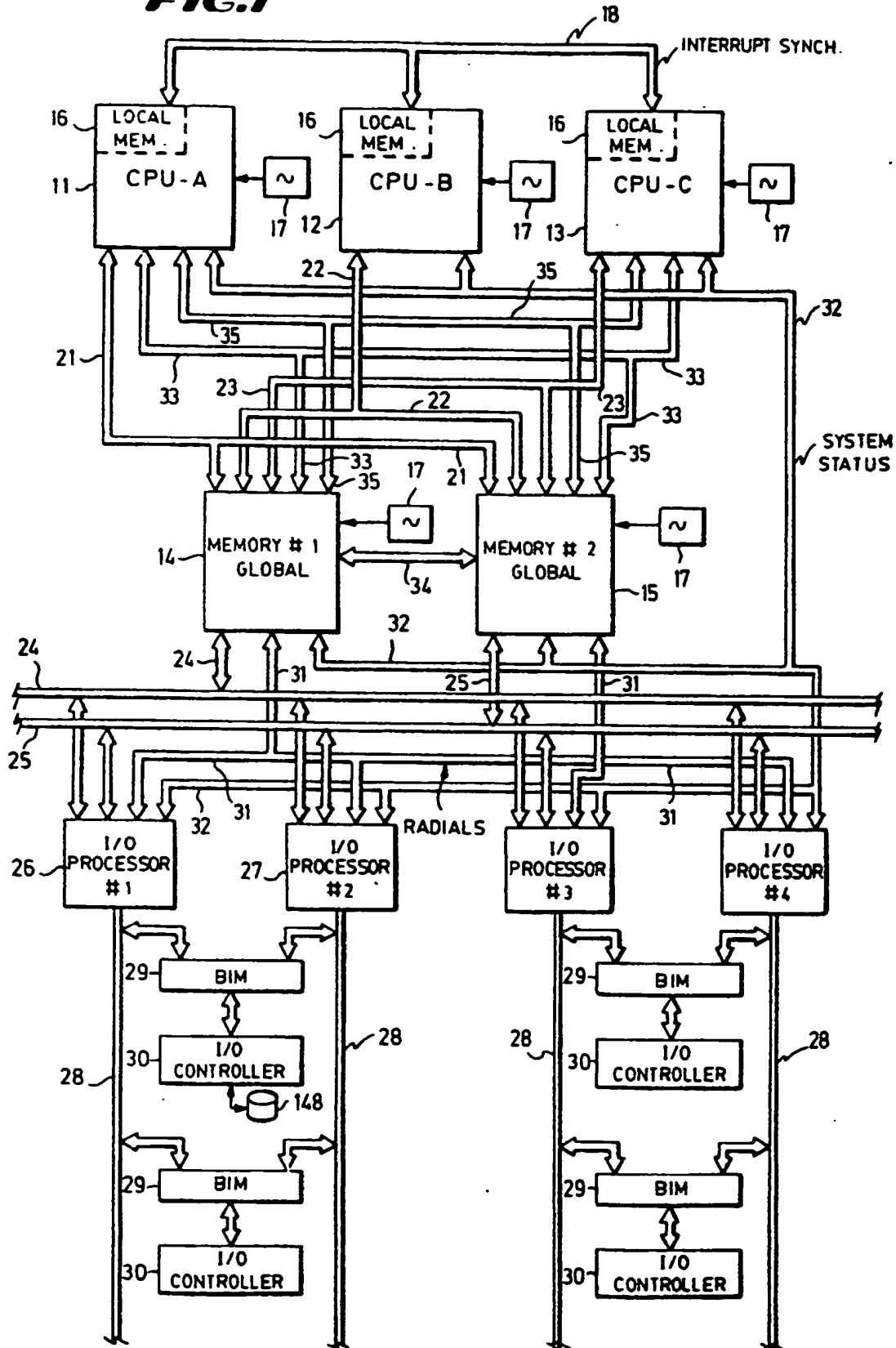
d) a first input/output bus coupled to said first memory unit and a second input/output bus coupled to said second memory unit;

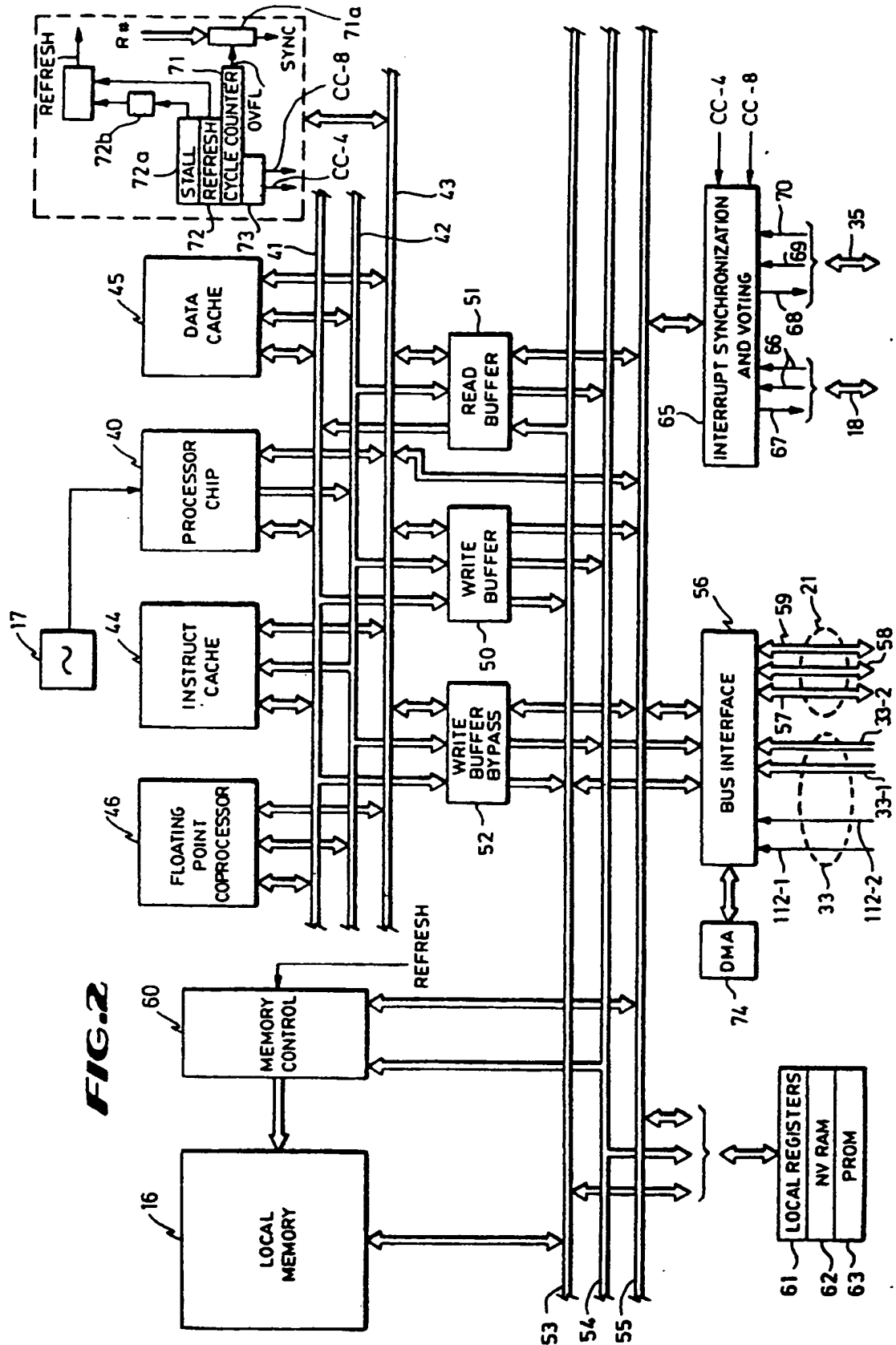
e) a first input/output processor coupled to both said first and second input/output busses, and a second input/output processor coupled to both said first and second input/output busses;

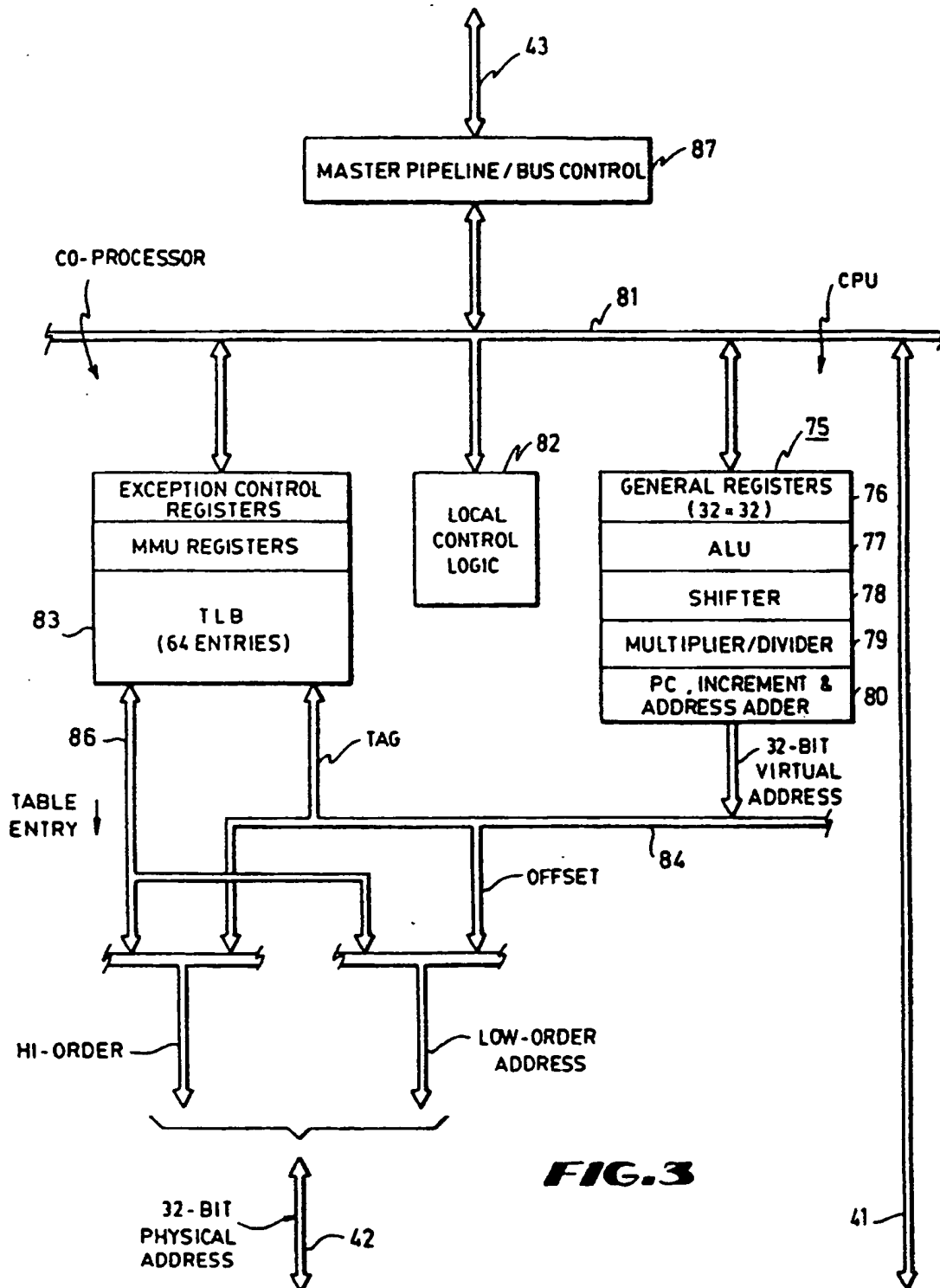
f) a file system having a directory with entries for each of said CPU units, each of said memory units, and each of said input/output processors; each of said entries being deleted from said directory if the corresponding CPU unit, memory unit or processor is placed offline.

48. A system according to claim 47 wherein said CPU units are executing a Unix operating system when executing said instruction stream.

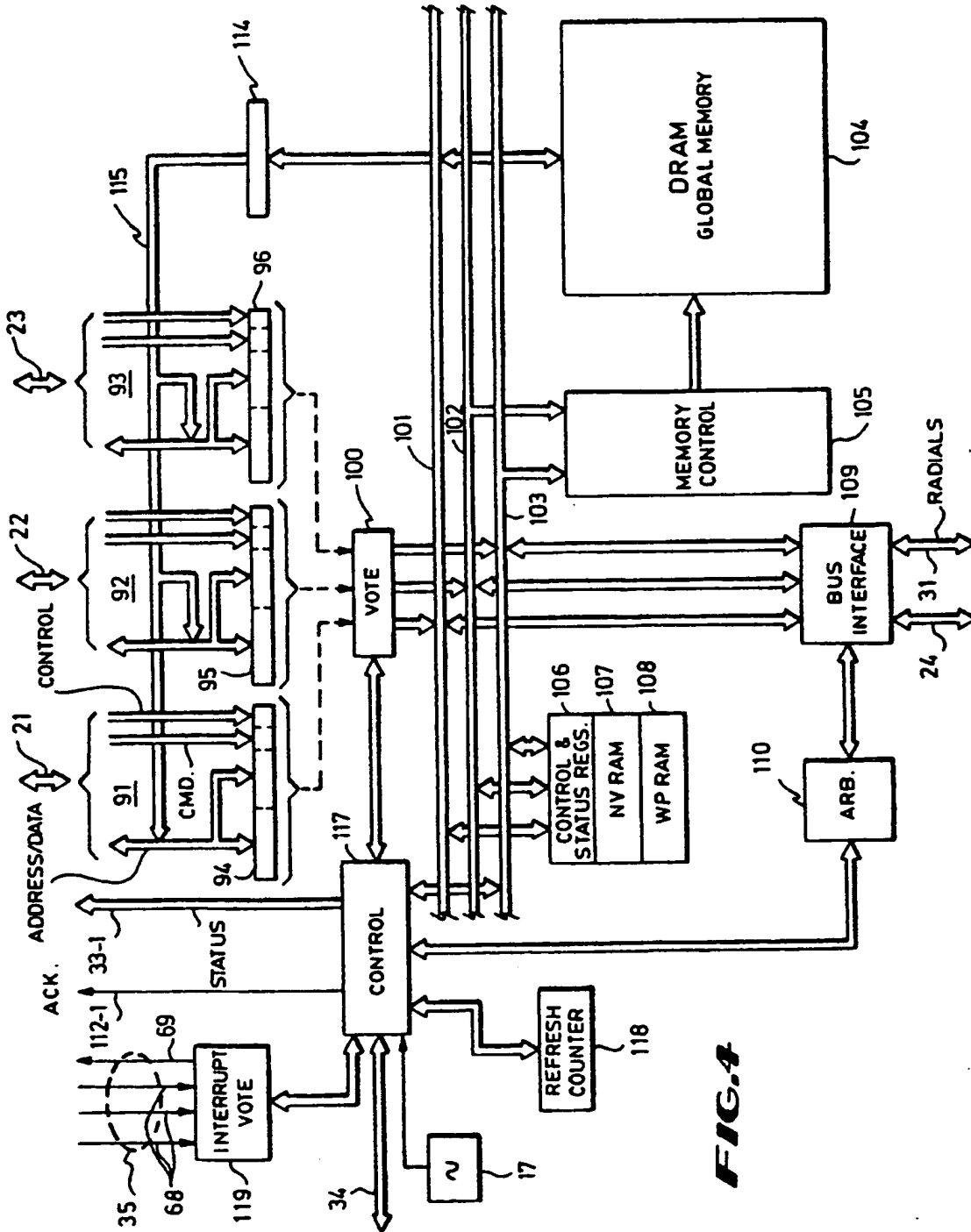
**FIG. 1**



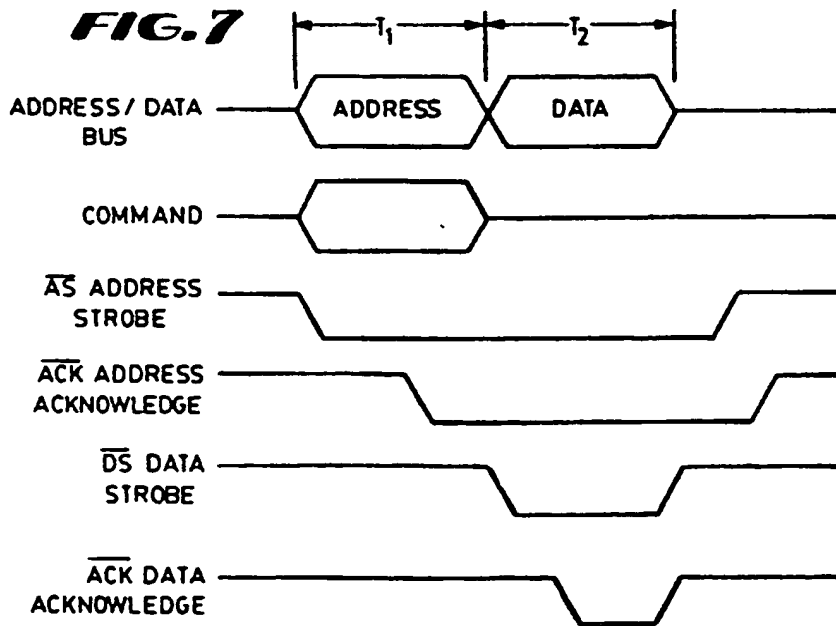
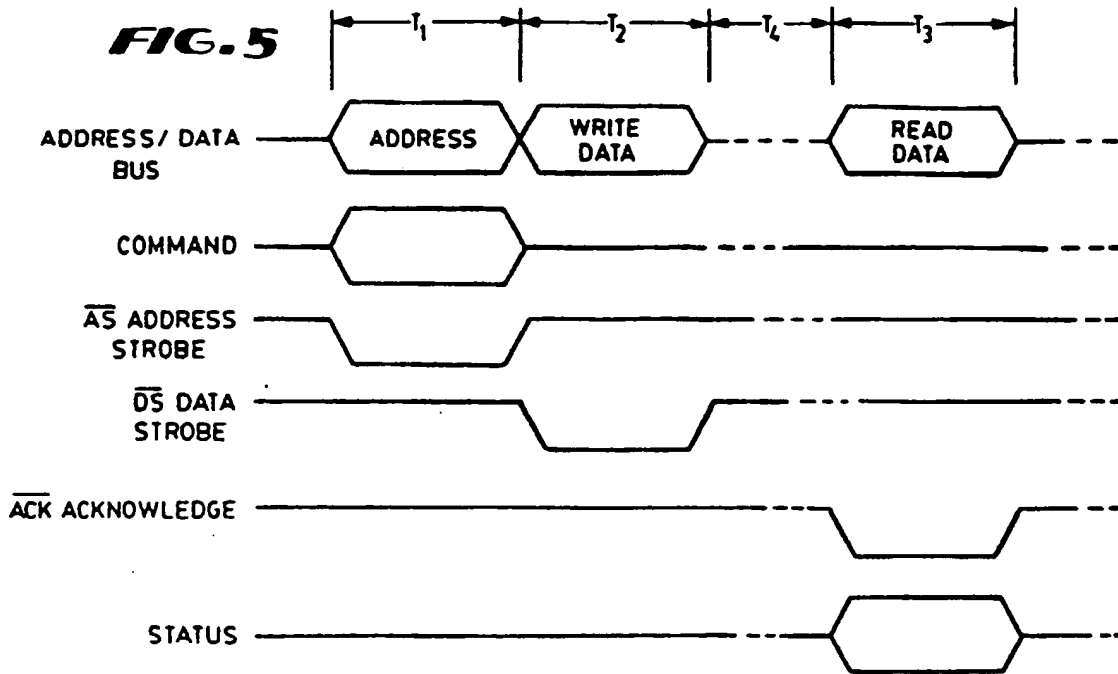


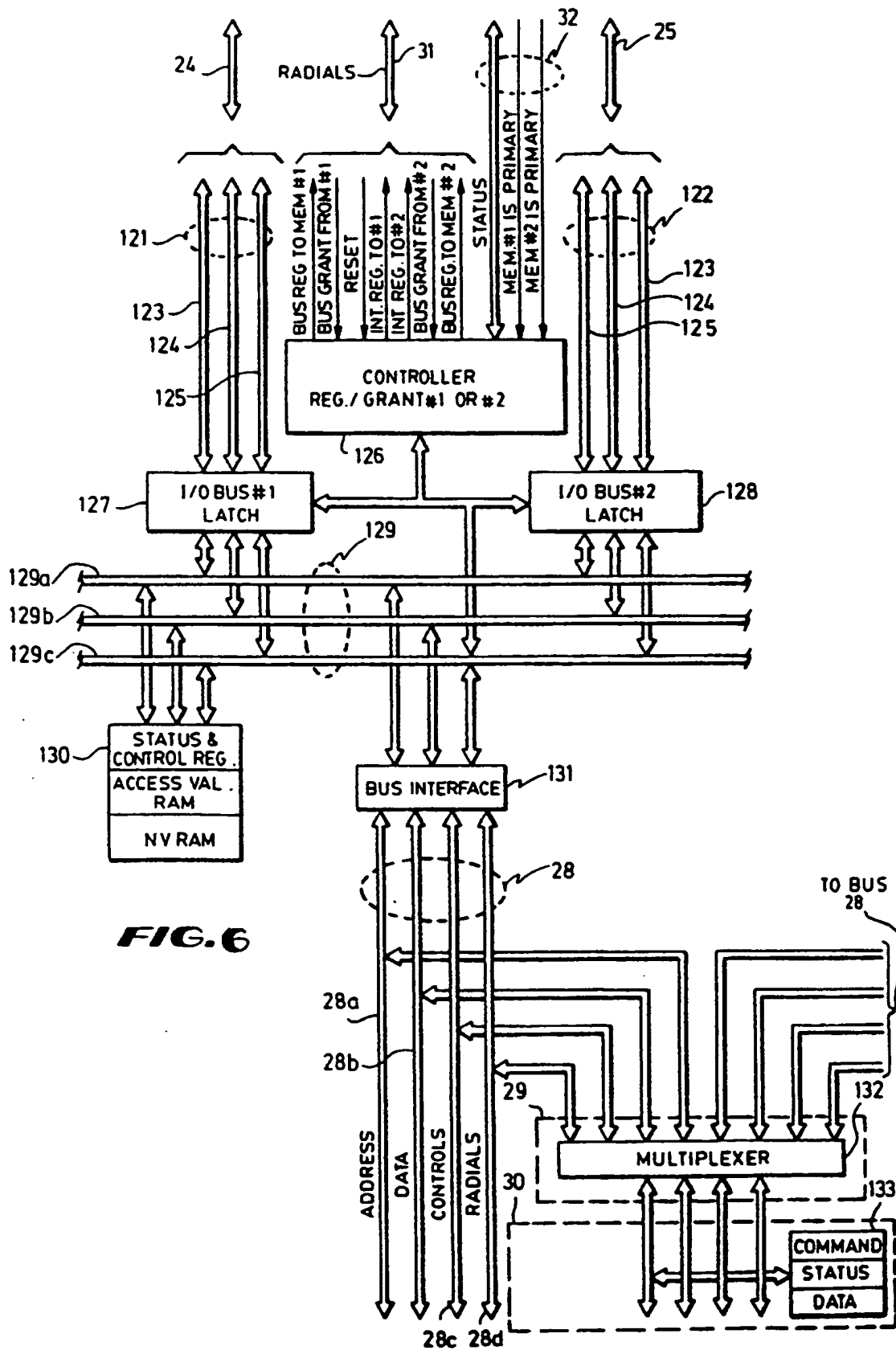


**FIG.3**

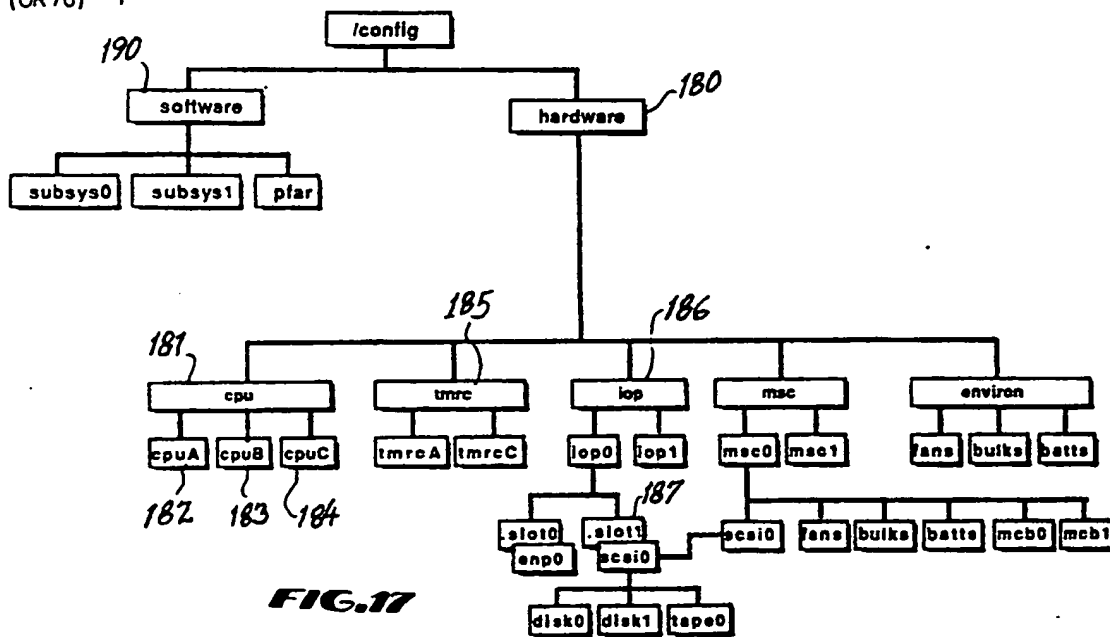
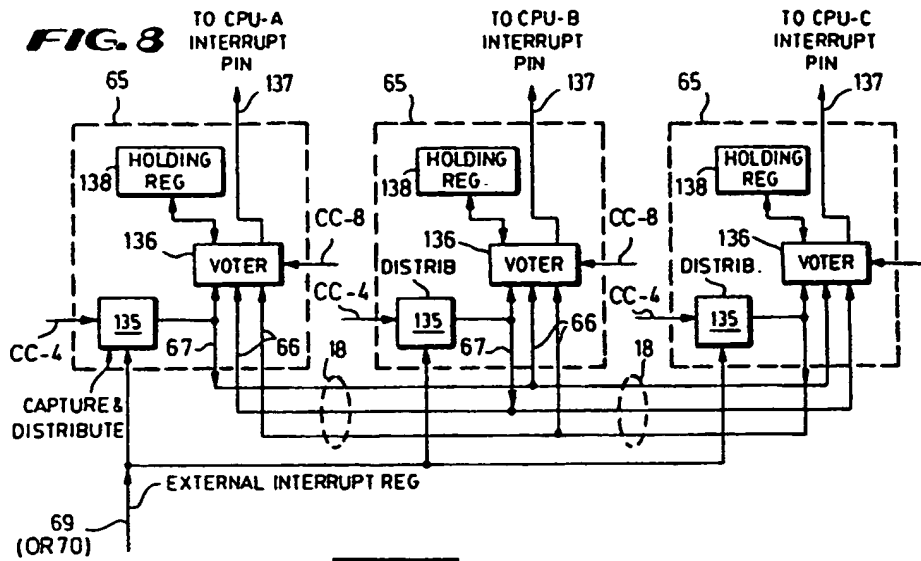


**FIG. 4**



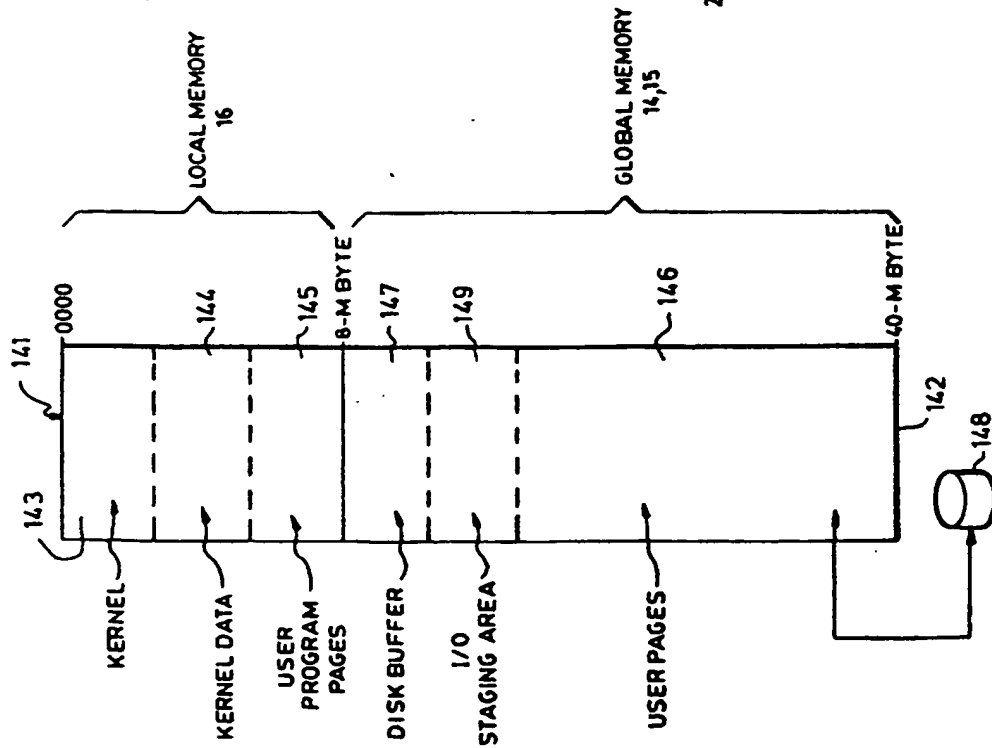


**FIG. 6**

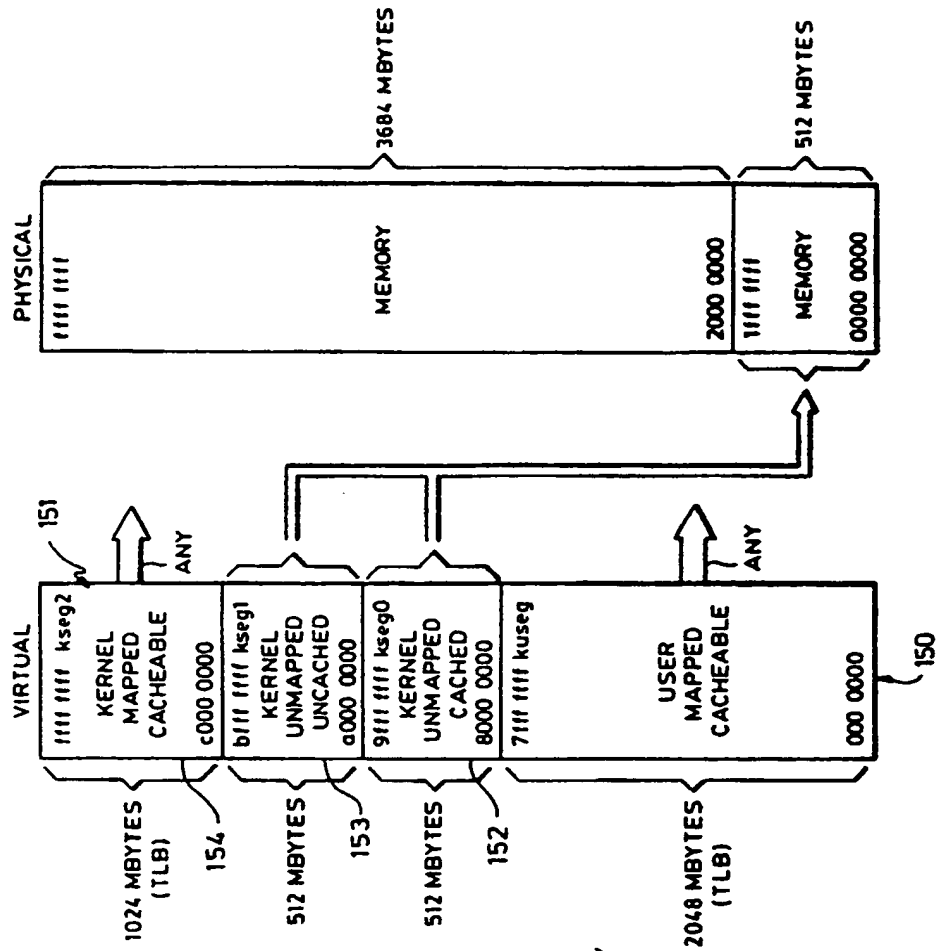


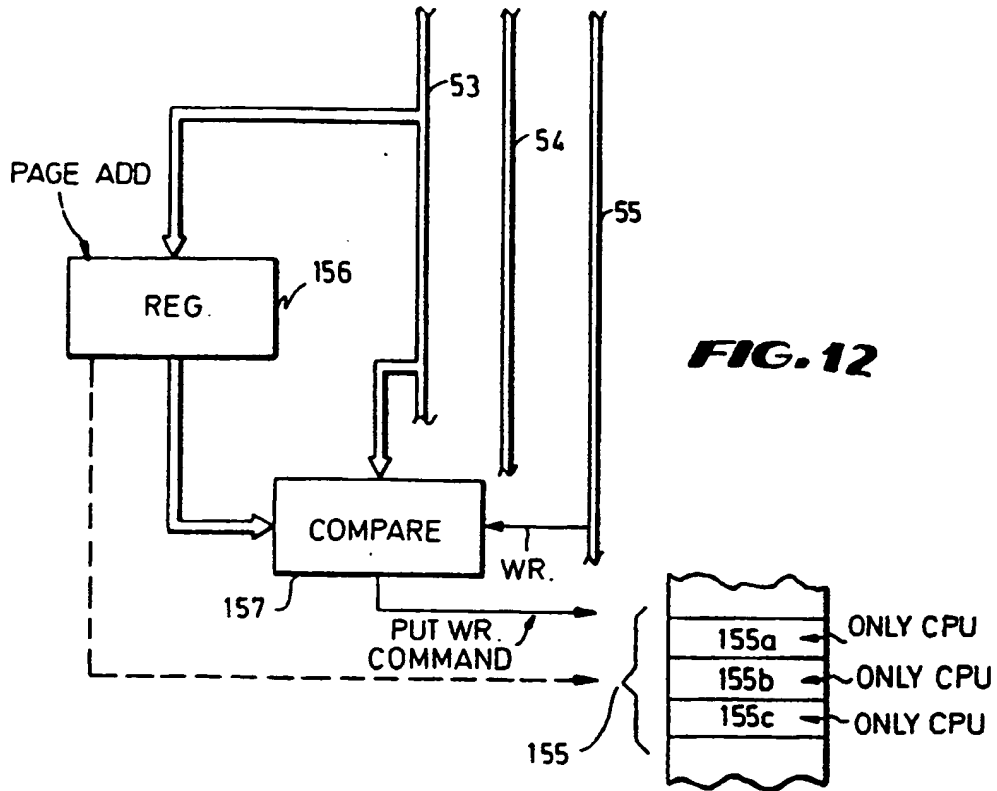


**FIG. 9**

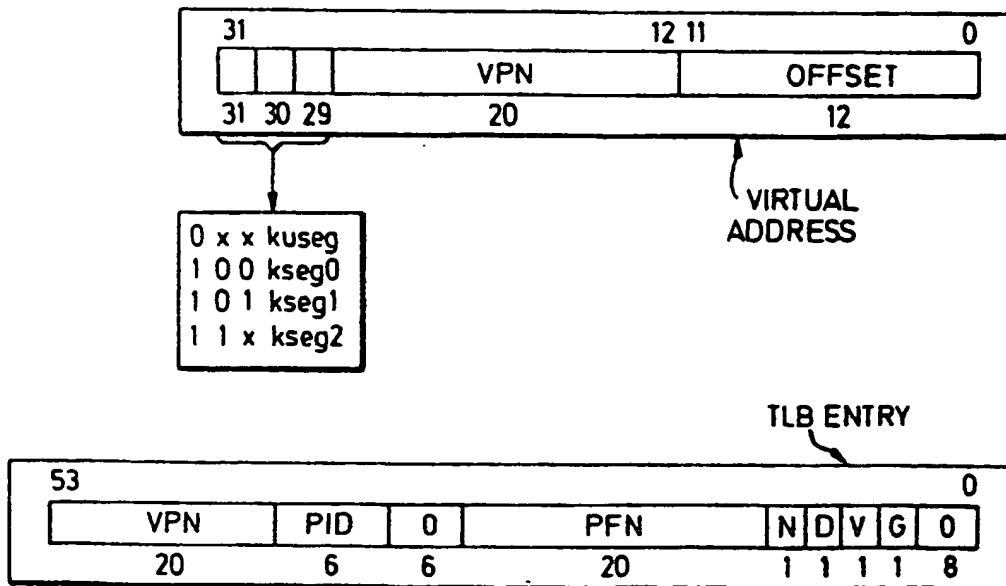


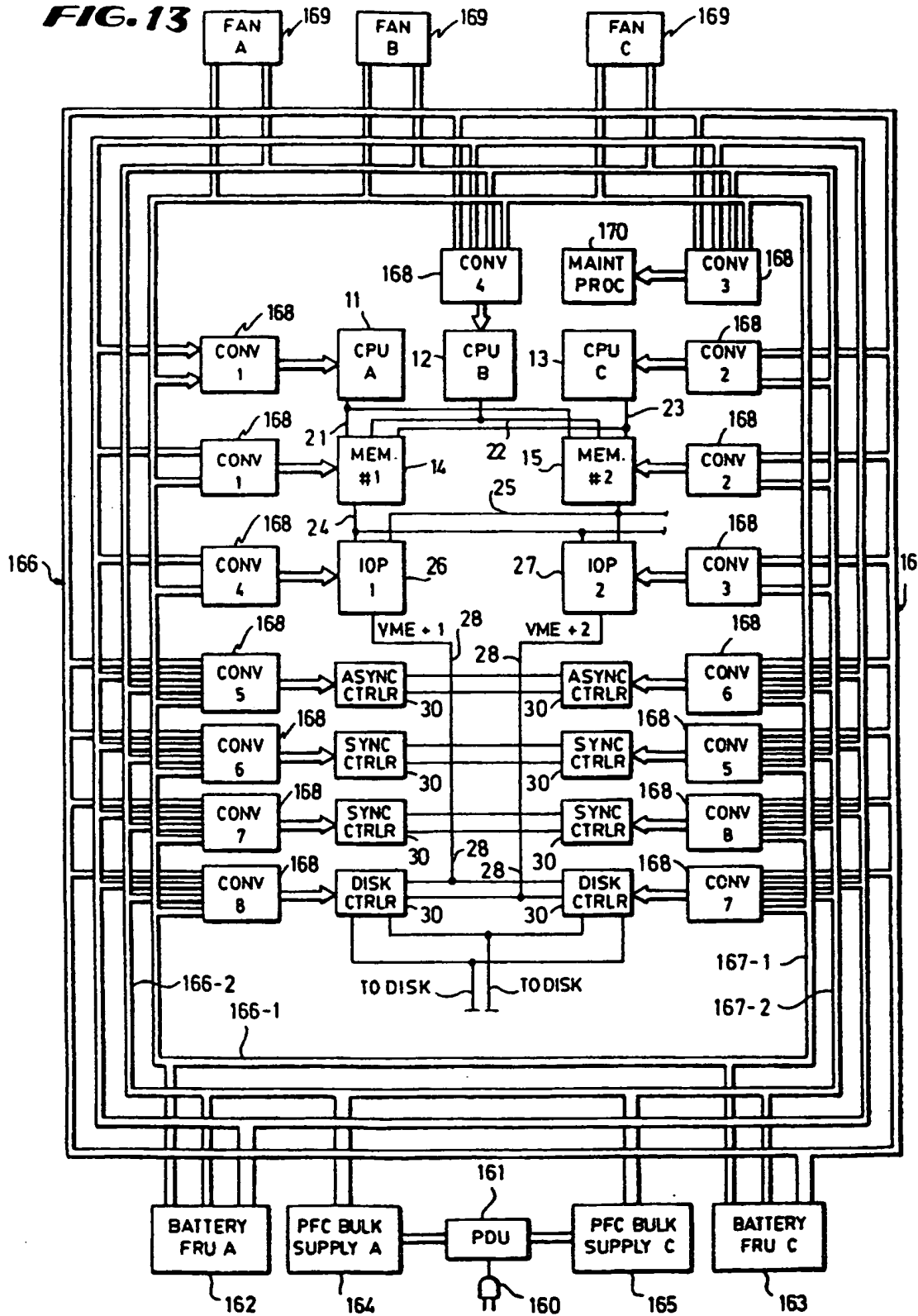
**FIG. 10**

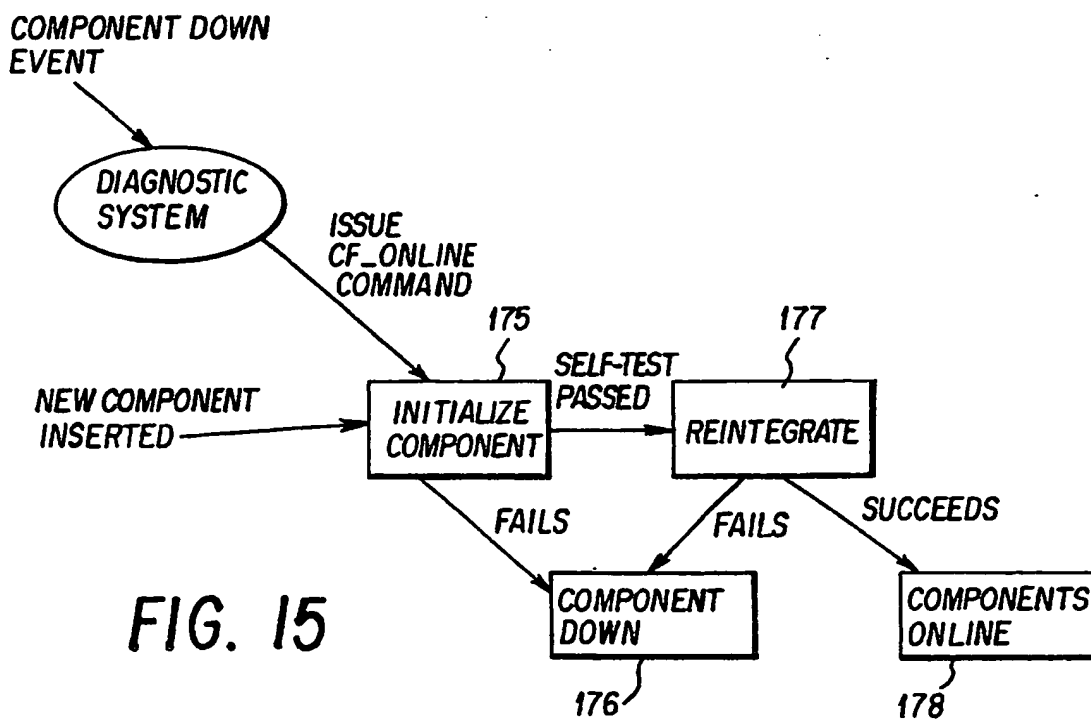
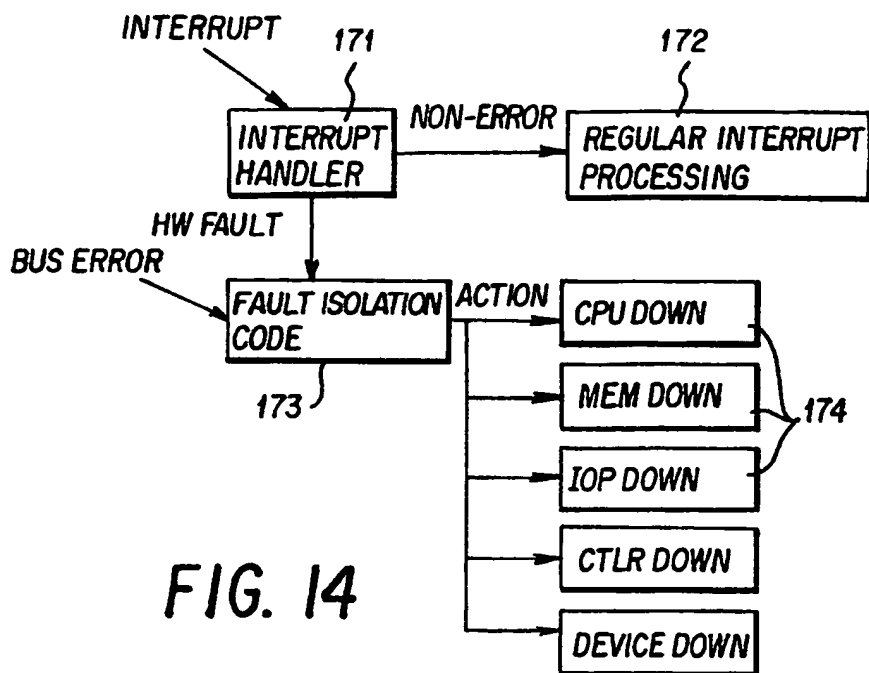


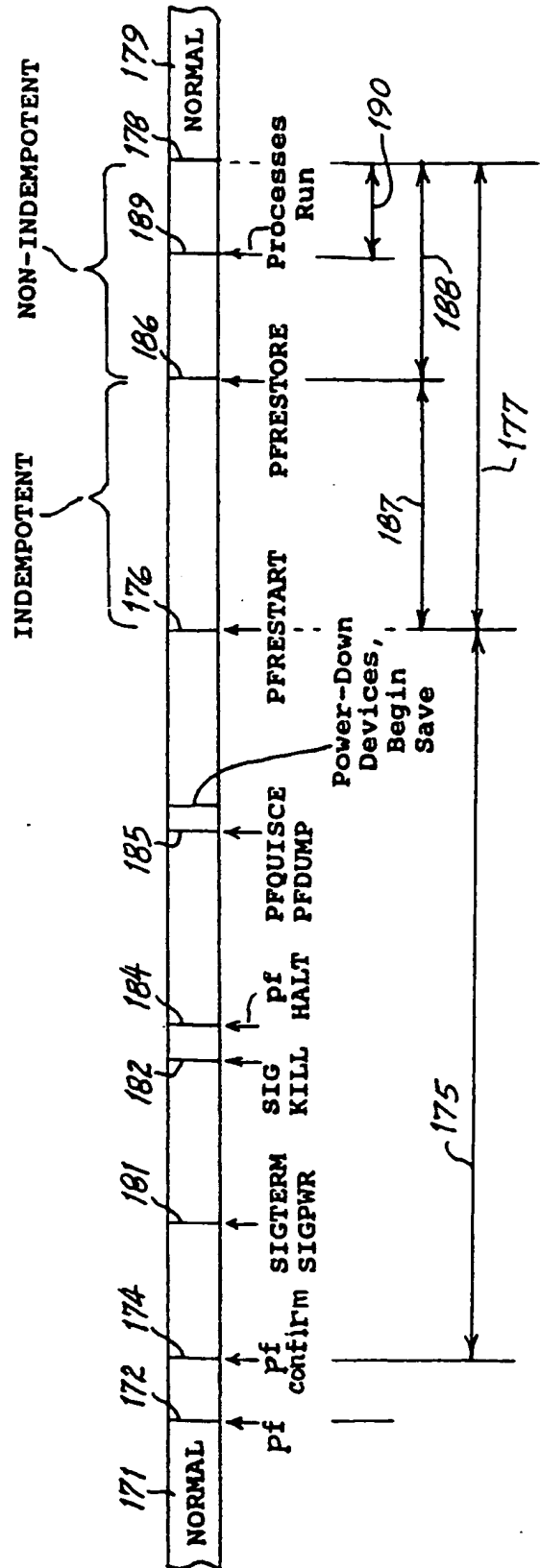


**FIG. 11**



**FIG. 13**





**FIG.16**

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